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# Structural Evaluation of Riveted Spillway Gates

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| | Problem Area | | Problem Area |
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| CS | Concrete and Steel Structures | EM | Electrical and Mechanical |
| GT | Geotechnical | EI | Environmental Impacts |
| HY | Hydraulics | OM | Operations Management |
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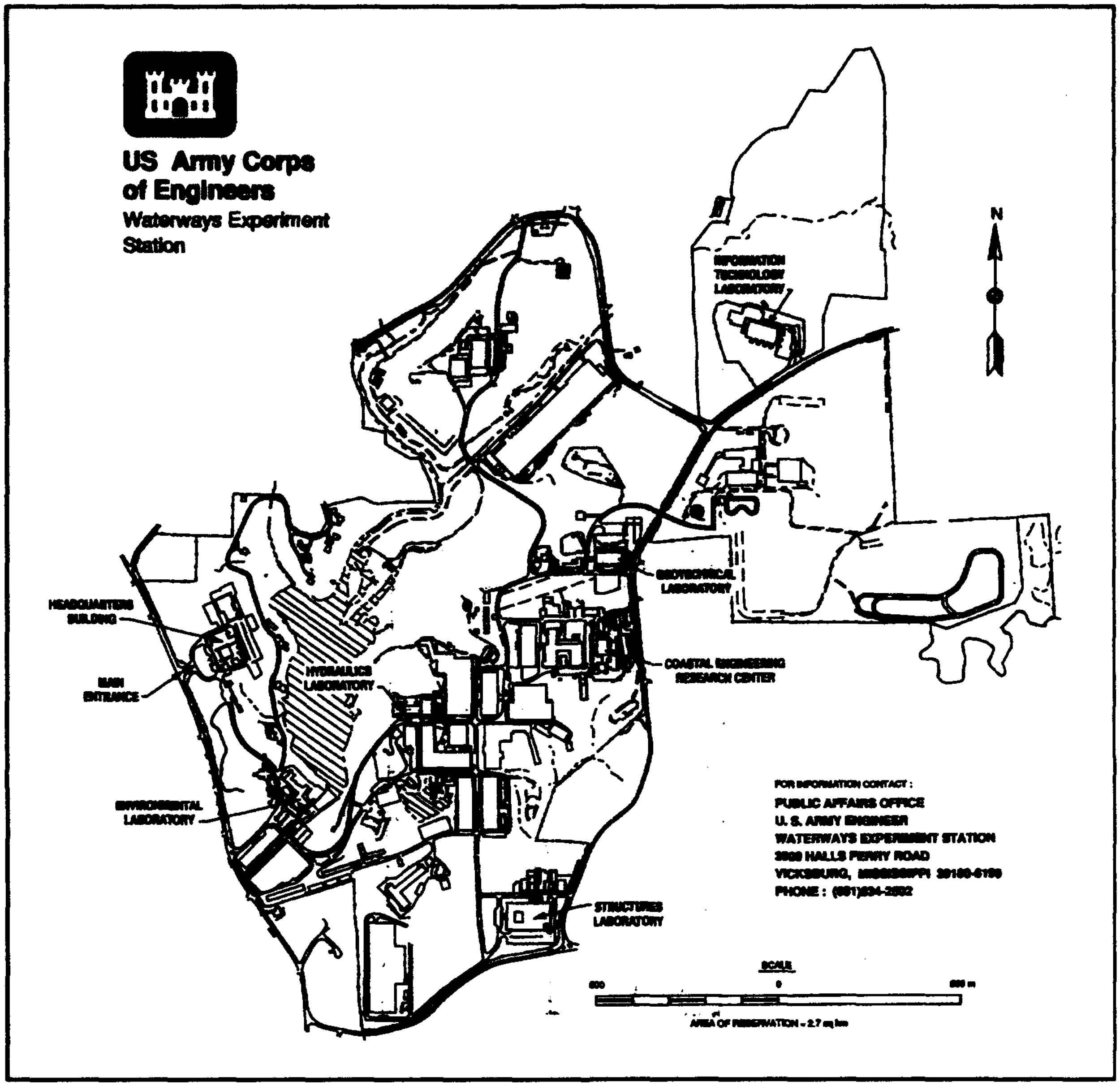


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# Preface

The work described in this report was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program and the Civil Works Guidance Update Program (CWGUP). The work was performed under the REMR Work Unit 32641, "Evaluation and Repair of Hydraulic Steel Structures," for which Mr. Cameron P. Chasten, Information Technology Laboratory (ITL), U.S. Army Engineer Waterways Experiment Station (WES), was Principal Investigator and the CWGUP project "Structural Evaluation of Existing Welded and Riveted Spillway Gates," for which Mr. Chasten also was Principal Investigator. Mr. Don Dressler (CECW-EP) was the REMR Technical Monitor, and Mr. William F. McCleese, Structures Laboratory (SL), WES, was the REMR Program Manager. Mr. Paul Tan (CECW-ED) was the CWGUP Technical Monitor for this work, and Mr. Thomas J. Mudd, ITL, WES, was the CWGUP Program Manager.

Mr. William N. Rushing (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-O) and Dr. Tony C. Liu (CECW-EG) served as the REMR Overview Committee. Mr. James E. McDonald, SL, WES, was the REMR Problem Area Leader.

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Acknowledgment is expressed to Mr. L. E. Bridges, U.S. Army Engineer (USAE) District, Mobile, Operations Division, for arranging and assisting in onsite inspections at the John Hollis Bankhead Lock and Dam on the Black Warrior River, and Messrs. Robert F. Post and Kent Hokens, USAE District, St. Paul, Engineering Division, for arranging and assisting in three onsite inspections at Mississippi River Lock and Dam Nos. 2, 5, and 9. Acknowledgment is also expressed to the Structural Evaluation Field Review Group (SEFRG), assembled to monitor this project, for providing assistance in this work. Members of the SEFRG and their affiliations are Messrs. Paul Tan, HQUSACE; Eugene Ardine, USAE Division, Ohio River; Frank N. Johnson, USAE District, Vicksburg; David J. Smith, USAE District, Omaha; and Thomas Sully, USAE District, St. Paul; and Drs. John J. Jaeger, USAE District, Jacksonville; John E. Bower, ATLSS, Lehigh University; and Chon L. Tsai, Ohio State University.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

# Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| Fahrenheit degrees | 5/9 | Celsius degrees or kelvins[1] |
| feet | 0.3048 | meters |
| inches | 0.0254 | meters |
| kips (force) per square inch | 6894.757 | kilopascals |
| miles (U.S. statute) | 1.609347 | kilometers |
| pounds (force) per foot | 14.5939 | newtons per meter |
| pounds per square inch | 6894.757 | pascals |

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

# Summary

The purpose of this study was to perform those tasks necessary to develop a set of guidelines that could be followed by Corps engineers to achieve a structural evaluation of riveted gates. This has been addressed through five tasks, identified herein as Tasks 1 to 5; a review of available drawings, documents, and literature relative to riveted gates; an onsite inspection of gates at sites selected by the Corps; a study of how corrosion might affect the gates; a study of loadings on the gates, especially repeated loadings; and, finally, the development of evaluation guidelines using the findings from the other tasks and an example application of the guidelines.

In Task 1, one objective was to gain insight into the design principles and materials that had been used for tainter, vertical lift, and roller type gates in the 1930's when many gates were constructed, insofar as these principles and materials affect evaluations and repairability today. Another objective was to determine what structural evaluations had been previously conducted and with what outcomes. It was determined that the riveted gates had been designed as statically loaded structures; whereas, more recent Corps documents reported that cyclic loads are occasionally induced due to flow-induced vibrations caused by passing water. It was also determined that buckling had occurred in gate members and that some retrofit modifications had been made to curtail further buckling. A review of steel standards suggested that the structural steels used in fabricating the riveted gates were generally not regarded as weldable steels, which suggests that repairs by welding should not be indiscriminately made on riveted gates.

In Task 2, ATLSS and Corps personnel made onsite inspections of gates on the Black Warrior and Mississippi Rivers and observed tainter, vertical lift, and roller gates. It was observed that a moderate amount of welding had been done on most riveted gates. The inspections also provided direct confirmation that vibrations were occasionally induced by the water flow; however, it was observed that a slight adjustment of gate position (with tainter gates) negated the vibration. Corrosion, accompanied by some degree of failure of the protective paint system, was prevalent on most gates.

In Task 3, the various forms of corrosion that can affect gates were identified and assessed for their likelihood. The prevalent forms are depicted in photographs taken during the onsite inspections. The most frequently observed form of corrosion was crevice corrosion; although pitting corrosion, galvanic corrosion, and general atmospheric corrosion were also observed. In general, gate corrosion was accompanied by a failure of the paint system. Therefore, factors important to effective paint systems are described. Additional factors affecting corrosion at gate sites are also described. Most of these are environmental: the pH of the river and of rain, river water content including ions such as deicing salts, film-forming materials such as oil, and biological organisms. Corrosion has an important role in a structural evaluation because it can lead, depending on circumstance, to loss of section, loss of strength, and diminished operability of the gate.

In Task 4, a general Corps concern about the effect of repeated loadings on riveted gates was examined. Although there may be several sources of repeated loading, the most potentially damaging is probably the flow-induced vibration that occurs when a tainter gate is open to some critical elevation (usually a few inches above the closed position). In the study, the fatigue strength of riveted members is discussed and related to standard categories of fatigue strength for welded details. It is concluded that when the calculated (or preferably measured) nominal stress range at a riveted detail does not exceed 6 ksi,[1] there is no concern for a fatigue failure no matter what the age of the gate. (In this study, gate stresses were not measured.) However, when the stress range is between 6 and 10 ksi, it is concluded that the fatigue strength of the riveted detail should be taken equal to that for a Type C welded detail; and if the stress range exceeds 10 ksi, the fatigue strength should be taken equal to that of the more severe Type D welded detail. Inasmuch as both groove welds and filleted tack welds were observed during the onsite inspections, the fatigue strength of these details should be equated to that of the even more severe Type E welded detail.

In the final task, Task 5, a procedure for conducting a structural evaluation is given. Four components of an evaluation are discussed: preinspection assessment, inspection, assessment, and recommendations for inspection, maintenance, and repair. For each component, the critical question to be addressed by an engineer is presented, and the factors that must be considered in his/her response are provided. The process is one of steps, in that an assessment cannot be made until the pre-inspection assessment and inspection are made; and the final evaluation cannot be made until all of the above are made. Included in Task 5 are discussions of the critical areas to be inspected and of techniques for conducting inspections. The fatigue inspection guide is based on the broad experience

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1 A table of factors for converting non-SI units of measure to SI is presented on page viii.

of Lehigh University personnel in inspecting bridges for fatigue cracks. Guidelines are also given relative to periodic inspections.

To illustrate how to apply the procedure, an example is presented based on the results of the inspection that ATLSS and Corps personnel made of riveted tainter gates at Lock & Dam No. 5 on the Mississippi River. Another example is presented assuming a new, more severe loading has occurred at the gates.

In concluding, it is suggested that the Corps' previous work in developing new reliability-based techniques for evaluating civil work structures be extended to spillway gates in a supplemental program.

# 1 Introduction

## Project Background and Purpose

This project develops practical guidelines for engineers involved in inspecting and evaluating existing riveted spillway gates. Within the scope of this project, spillway gates are hydraulic structures used as damming gates on a river to control the flow of water at a lock and dam. Several types of spillway gates are prevalent, including tainter gates, vertical lift gates, and tube-type roller gates.

Newer spillway gates are typically fabricated of welded structural steel. However, the older gates, most of which are still in use, are of riveted steel construction. A major concern today is the structural reliability of these older riveted gates. Many of them were fabricated and placed in service in the 1930's and earlier and, thus, may have severely deteriorated and damaged components. Moreover, their service requirements may have gradually become more severe than their original design anticipated. A significant amount of cyclic loading may have occurred; corrosion and cracking at and near the rivets may have occurred; and buckling or other distortion may have occurred.

Other differences also exist between older riveted gates and newer welded gates. New gates can be expected to be fabricated from metallurgically cleaner and mechanically tougher metals than their older riveted predecessors. Furthermore, new gates are most assuredly being more thoroughly analyzed with computer-assisted computational techniques such as finite element methods. And, the knowledge base available today for the strength and life of riveted structures is significantly greater than when riveted construction was common because of major studies that have been completed on riveted bridge structures.

For these reasons, and because spillway gates constitute a substantial number of existing hydraulic structures, a method of conducting an effective structural evaluation of riveted spillway gates is of major importance. Therefore, this project was initiated to develop guidelines for conducting such a structural evaluation. For the purpose of the project, a structural evaluation is the process of determining the structural adequacy of a gate

for its intended use, including the assessment and remediation of limiting conditions.

## Project Scope

In conducting this project, five tasks were incorporated into the program:

*a.* A review of salient documents and drawings provided by the Corps and/or available in the literature.

*b.* A site review of gates selected by Corps personnel.

*c.* A study of the environmental effects on gates, related to corrosion.

*d.* A study of repeated loadings on gates, and a study of the strength of riveted structures under fatigue loading.

*e.* The development of evaluation guidelines using the results of the aforementioned tasks.

The tasks and a brief description of each task are provided in the following paragraphs.

### Task 1 Review of Literature

To achieve a structural evaluation of riveted spillway gates, it is necessary to review the critical structural concerns for riveted construction, to apply the currently available design knowledge base to them, and to develop practical guidelines for engineers and inspectors to use in their assessment of the gates.

With this in mind, a review of available descriptive and design data for riveted spillway gates was made to determine the types of members and details contained in these structures, the nature of the loadings on the gates, and the types of cracks or other distress that have occurred.

In addition, other salient, published literature, including patents, pertaining to spillway gates and inspection and assessment techniques for existing structures was reviewed. Moreover, a review was made of the American Society for Testing and Materials (ASTM) steel specifications that were standard when many riveted gates were designed and fabricated.

### Task 2 Site Review of Gates

Riveted vertical lift and welded tainter gates were visited and inspected at the John Hollis Bankhead and Holt Lake Lock and Dams on the Black Warrior River, and riveted tainter and roller gates were visited and inspected at Lock and Dam Nos. 2, 5, and 9 on the Mississippi River. Findings from these visits were used to identify loadings, practices, and problems and to both develop and validate the evaluation guidelines.

### Task 3 Environmental Effects on Gates

Because corrosion can adversely affect gates, a determination was made of the different types of corrosion that can potentially occur and of appropriate identification and assessment techniques. The environmental effects of water and air quality related to corrosion were also considered.

### Task 4 Effect of Repeated Loadings on Gates

Corps personnel had suggested that fatigue considerations may be important for gates. Therefore, in this task, sources of repeated loadings on gates were reviewed and then fatigue data were applied to riveted gate details. A significant database on the fatigue behavior of riveted steel structural members exists, and much of these data, although derived mostly from studies on bridge members, are transferrable to riveted spillway gates. Some welded details were also examined when these details were normally used with riveted gates, such as certain seal welds and tack welds.

### Task 5 Structural Evaluation Guidelines

In this task, the most compelling of the tasks, guidelines for a structural evaluation have been developed by identifying and discussing four primary steps in an evaluation: (a) preinspection assessment, (b) inspection, (c) assessment, and (d) recommendations for inspection, maintenance, and repair. For each step, the primary question to be asked is presented and alternative responses are discussed, leading to a judgment on actions to be taken relative to the structural adequacy of the gate. Critical sites to be inspected for corrosion and fatigue damage are identified, and inspection procedures are described.

Illustrative structural evaluations are also presented to demonstrate the proposed guidelines. The examples, one actual and one assumed, are based on one of the tainter gates on the Mississippi River. Finally, recommendations for continuing evaluations are presented.

# 2 Task 1 - Review of Literature

As the initial task, a review was made of spillway gate descriptions, their design criteria, and other literature that could be provided by the Corps or that was published. The objectives of this task were to determine what structural considerations and material properties are involved with riveted spillway gates, what prior structural conditions and problems have occurred, and what causes and effects have been noted. It is reasonable that these earlier findings might affect current and future structural evaluations.

## Literature on Gates

In this review, documents relative to tainter gates, vertical lift gates, and roller gates are considered. In addition, documents describing some special loadings, such as ice loading and dynamic loading, and structural problems attributed to these loadings, are reviewed.

### Tainter gates

In 1879 - 1881, Mr. J.B. Tainter and his partners developed improvements to the design of sluiceway gates and arrived at new designs which would later carry his name and be called tainter gates. Those new design ideas were patented (Tainter and Parker 1879; Parker et al. 1880; Tainter 1881), and one of Tainter's gates is illustrated in Figure 1.

More than 60 years later, the Corps of Engineers had designed a simplified and lighter tainter gate (Figure 2), but one that retained many of Tainter's original principles (Brizzel 1948). The major evolution during this period included the following: (a) in material, steel was used instead of timber, (b) in design, trunnion and hoist mechanisms were refined, and (c) rivets and/or welding replaced other mechanical fasteners.

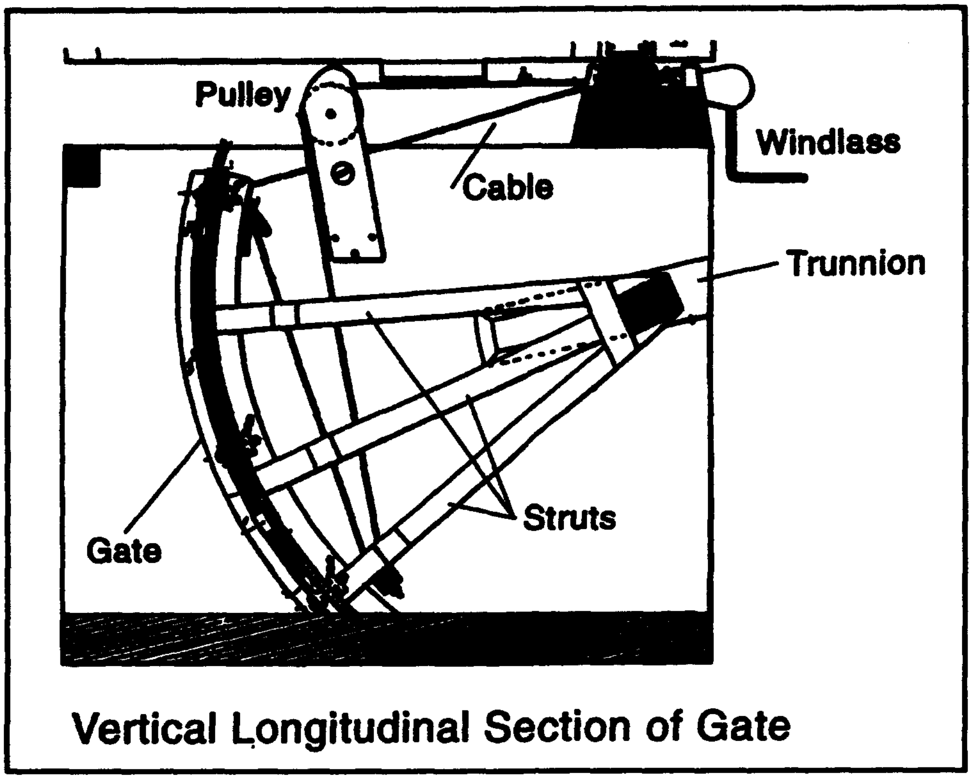


Figure 1. Gate section patented by J. B. Tainter in 1880

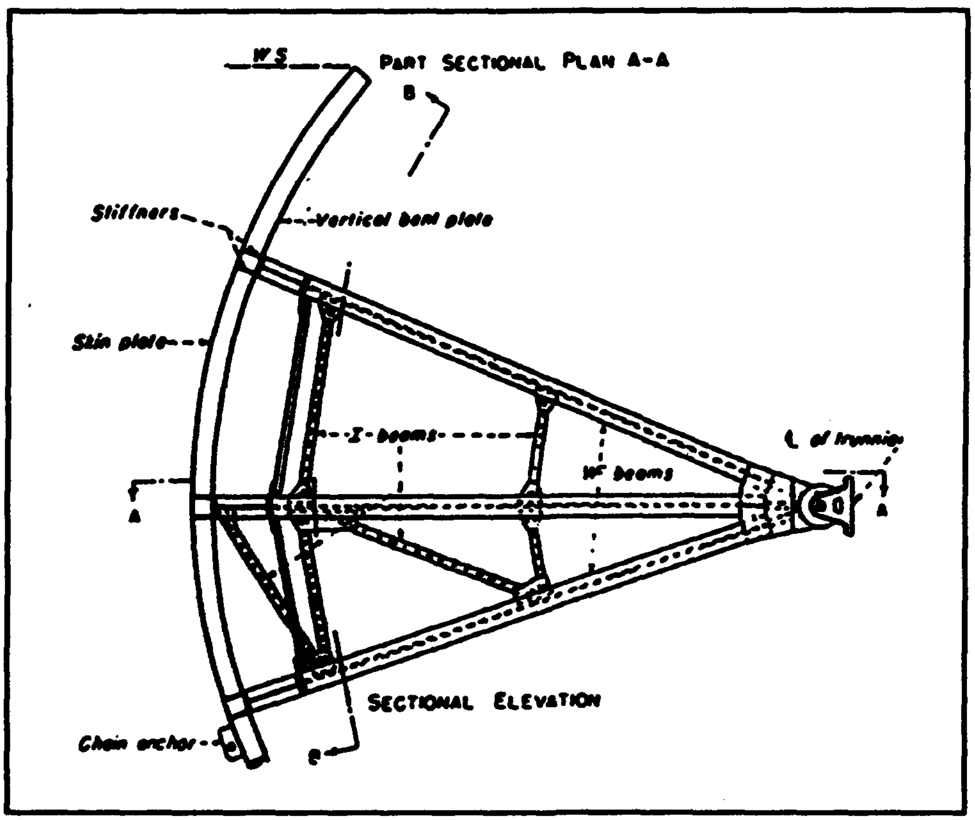


Figure 2. Simplified tainter gate in 1940's

The tainter gate is often considered the most economical and usually the most suitable type of gate for controlled spillways because of its simplicity, light weight, and low hoist-capacity requirements.

The principal elements of a typical tainter gate structure are the following:

*a.* Skin plate assembly, consisting of a skin plate stiffened by curved vertical ribs. The skin plate forms the damming surface and is shaped in a circular arc.

*b.* Two or three horizontal girders, with the horizontal girders supporting the skin plate assembly and transferring the forces due to the pool pressures and cable loads to the end frames.

*c.* End frames, consisting of girders or struts and strut bracing. The end frames transmit forces to the trunnions.

*d.* Trunnion assembly, consisting of a trunnion hub with bronze bushing and heavy flanges, a trunnion yoke, and a trunnion pin. The trunnion assemblies transmit the forces from the end frames into the supporting pier.

*e.* Seals (at side and bottom), usually rubber. The seals prevent the water from passing at the periphery of the gate.

*f.* Hoist, consisting of chain, link, or wire-rope assemblies at either end of the gate connected to the skin plate. The hoists are used to raise and lower the gate.

Some aspects of the principal elements that must be considered during inspection and evaluation (U.S. Army Corps of Engineers 1966, 1991; Dressler 1976) are:

*a. Skin plate.* The minimum thickness at the top is usually 3/8 in., increasing with depth but rarely thicker than three fourths in. In the zone of contact with the hoist cables, the skin plate is reinforced. The upstream surface has mostly submerged or splash exposure while the downstream surface has more atmospheric and splash exposure with less submerged exposure.

*b. Ribs.* These are skin plate stiffening members mounted on the downstream side of the skin plate. Particular attention should be paid to ribs which are near the lifting cables since high concentrated loads may be applied.

*c. Horizontal girders.* These girders are the primary load-carrying members which support the skin plate-rib assembly. They are oriented with their webs in radial planes. Consequently, drain holes are

placed in the webs to prevent ponding of water and should always be kept open to avoid corrosion.

*d. End frames.* The primary end frame members are usually horizontally oriented girders. The drain holes in their webs should always be kept open.

*e. Trunnion assembly.* Pin friction can be high and may induce high stresses in the end frame members. Therefore, trunnion lubrication is critical. The flanges of trunnion assemblies are usually configured to align with the end frame girders.

*f. Seals.* The side seal rubbing plates should be kept clean and smooth to prevent corrosion and should be free from ice. There is movement between the bottom seal and its contact plate due to the live load deflection of the ribs and the girders. For gates which are operated in subfreezing weather, it is necessary to deice the seals so that gate operation can be maintained. The deicing is done by electric heaters or air deicing devices.

*g. Hoist.* The chain or wire rope should contact the skin plate closely for essentially the full height of the gate. The hoist cable is a nonredundant member; therefore, it should be kept in good condition with little corrosion.

## Vertical lift gates

It is sometimes preferred to use vertical lift gates instead of tainter gates in the following circumstances (U.S. Army Corps of Engineers 1962):

*a.* The elevation of the maximum controlled pool is so far above the sill that excessively large piers would be required for tainter gates.

*b.* Flood discharges or drift conditions are such that any obstruction to flow below the bottom of the spillway bridge is undesirable.

*c.* There is an overall economic advantage due to the speed of erection of vertical lift gates and consequent shortening of the construction time for the project as a whole.

Vertical lift gate assemblies are illustrated in Figures 3-5. Defined in terms of how the water load is transferred to spillway piers, there are three types of gates:

*a. Fixed-wheel gate (Figures 3 and 4).* The wheels revolve on fixed axles mounted on the end frame of the gate. This is the most common lift gate and is adaptable to long spans and a heavy moving load. This type of gate was observed on the Black Warrior River (see Chapter 3).

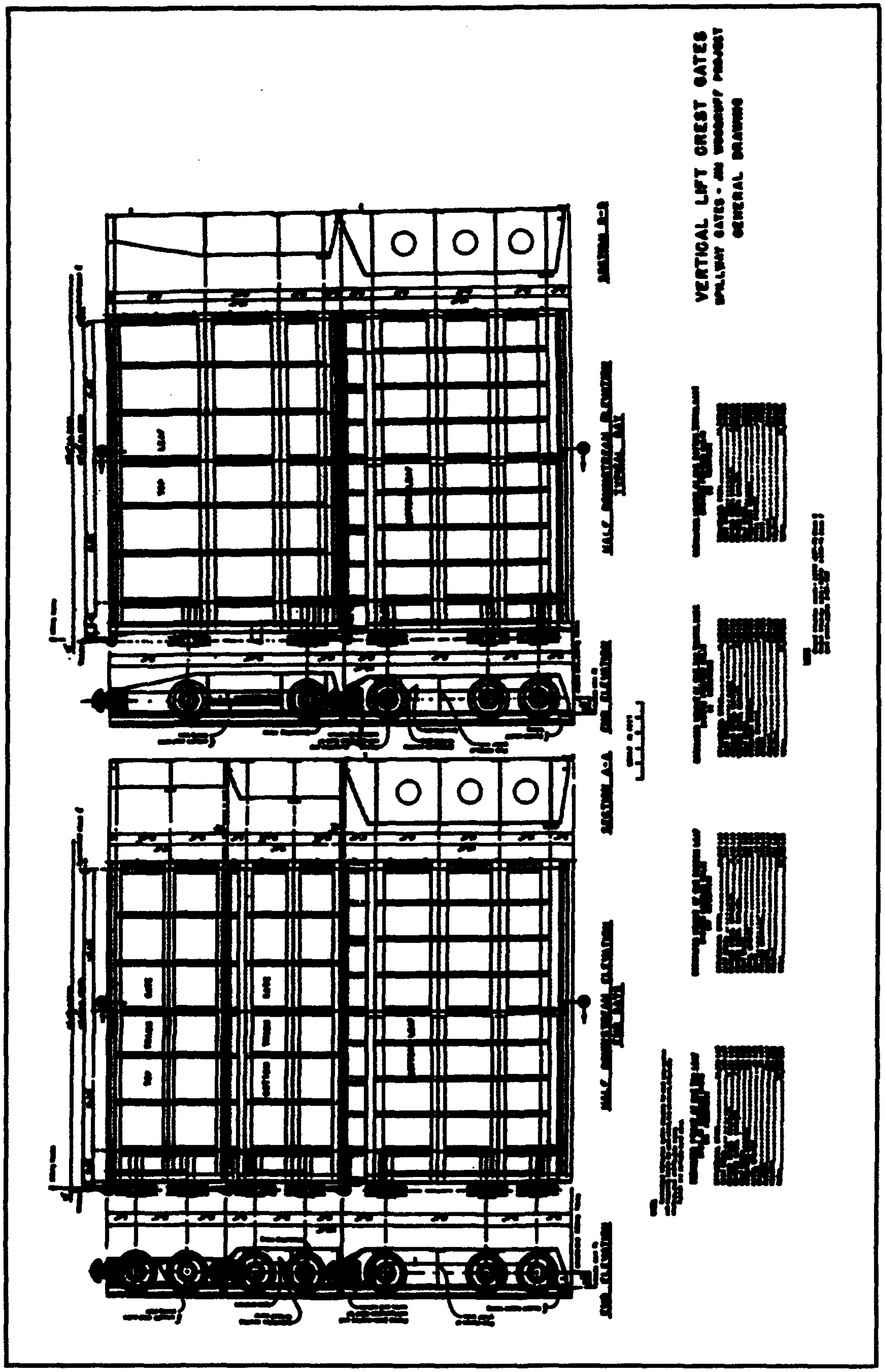


Figure 3. Large, multiple section, vertical lift, fixed-wheel gate

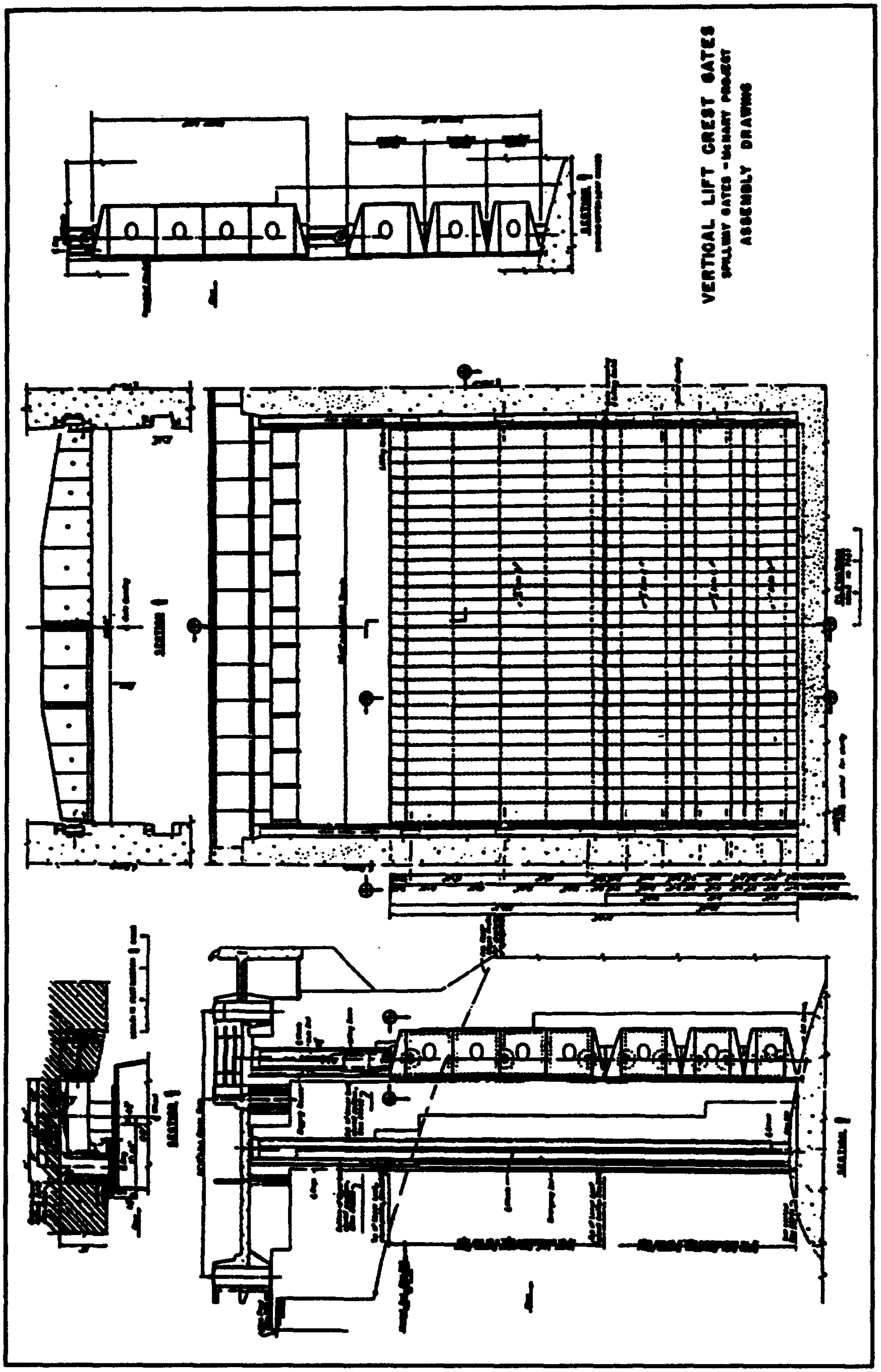


Figure 4. Smaller, double section, vertical lift gate with fixed-wheel showing wheel track

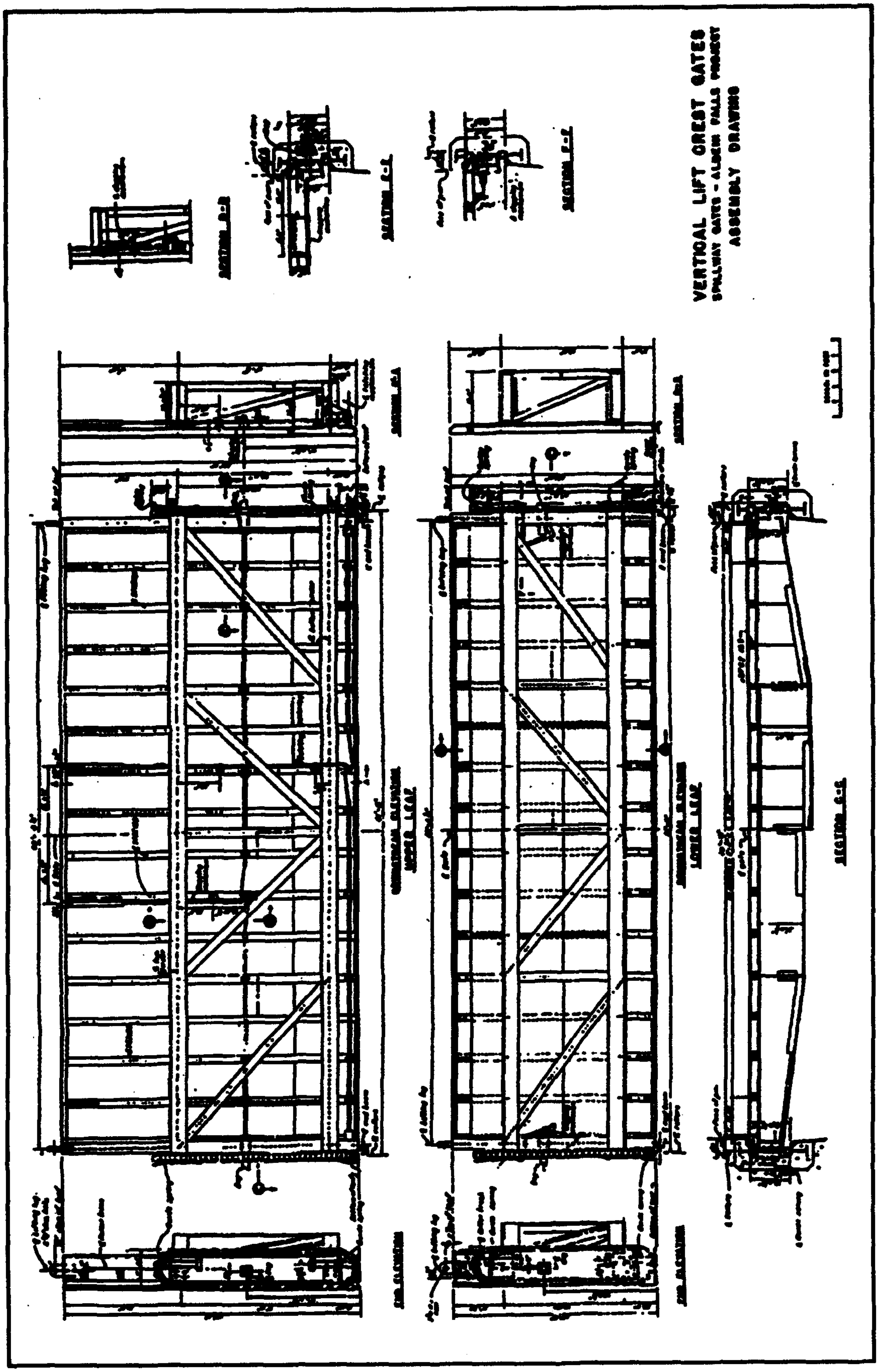


Figure 5. Vertical lift gate with tractor

b. *Tractor gate (Figure 5).* Gate lifting relies on one or more endless trains of small rollers supported by the gate's end frames. Although this type of gate has the advantage of low friction component of lifting load, it is still not popular because it has low tolerances and demands high precision.

c. *Stoney gate.* A train of the rollers between gate and pier is supported independently. Owing to complicated operation, it is very rarely used.

The vertical lift gates can also be classified by construction:

a. Single section gates, as observed on the Black Warrior River.

b. Multiple section gates in the same slot.

c. Double section regulating gates in adjacent slots. These are seldom used because of their more complicated operation and larger pier requirement.

The principal elements of a vertical lift gate structure are the following:

a. *Skin plate with vertical beams.* The minimum skin plate thickness is 3/8 in. Intercostals, or secondary stiffeners, are used where the girder spacing is large and at the bottom portion of the gate to strengthen the skin plate assembly.

b. *Horizontal girders.* Horizontal girders are primary load-carrying members. They support the skin plate assembly and frame into end posts at the slots.

c. *End bearing assembly.* This assembly includes the end posts and a number of wheels or rollers which transfer the girder reactions from the end post to a vertical track on the pier. Wheel alignment and the track surface accuracy are a major concern to prevent local overload. Proper lubrication and sealing are essential where either sleeve or antifriction bearings are used.

d. *Seals.* The side seals always include J-type rubber as the watertight device. If the gate and sill are carefully fabricated and properly installed, a bottom rubber seal is not required. For multiple section gates, the horizontal rubber seal between gate sections is necessary and must be mounted and fastened sturdily to withstand the impact of the water flowing between the sections when the upper section is raised. The surfaces against which the rubber seals bear should be as smooth as possible and resistant to corrosion. Icing is prevented by the same heating or deicing methods employed with tainter gates.

*e. Lifting arrangement.* The lifting hooks attached to the gate and their connections to the gate are of primary importance, since their failure would cause the gate to be inoperable. The lifting arrangement must always be well maintained.

*f. Dogging arrangement.* Lift gate sections are provided with dogging seats on the end posts, see Section C/2 in Figure 4. Dogs are usually mounted on grillages in the piers. They are pivoted and operated through push rods by levers at the deck level. Lubrication by piping is required.

*g. Tracks.* The tracks are constructed with either heavy, flat, corrosion-resisting plates or railroad rails. In either case, the track surface is hardened and must be maintained essentially flat.

*h. Guides.* Structural steel guide members limit the movement of the gate horizontally either in the upstream direction or sideways.

*i. Sill.* The sill is generally a steel H section set in a block-out in the concrete of the spillway. The exposed upper surface of the top flange is generally corrosion-resisting steel.

## Roller gates

*Roller gates* are usually designed for spillways with large distances between piers. The typical roller gate consists of a long horizontal cylinder with an attached apron (Figure 6). The cylinder is attached to end disks at each end which bear against inclined racks on the sides of each pier (Figure 7).

The primary structural members of a roller gate are the following:

*a. Drum assembly.* The drum assembly is a large cylinder which acts as a beam and torque tube to carry the hydrostatic and dead loads. The skin of the cylinder is stiffened by equally spaced stiffeners or ribs. The stiffeners are braced at intermediate points along the length of the drum by a truss-type assembly. The hydrostatic and dead loads are transferred to the end disks.

*b. Apron assembly.* The apron assembly is an extension of the damming surface. It consists of a skin plate extending outward from the cylinder and supported by horizontal ribs and a truss bracing assembly. The connections between the drum assembly and the apron assembly are the transition area which needs to be inspected carefully.

*c. End disks.* The skin plate and horizontal stiffeners transfer load into the end disks which are essentially truss-type configurations. The loads are then transferred from the end disks to the lifting chains and the piers.

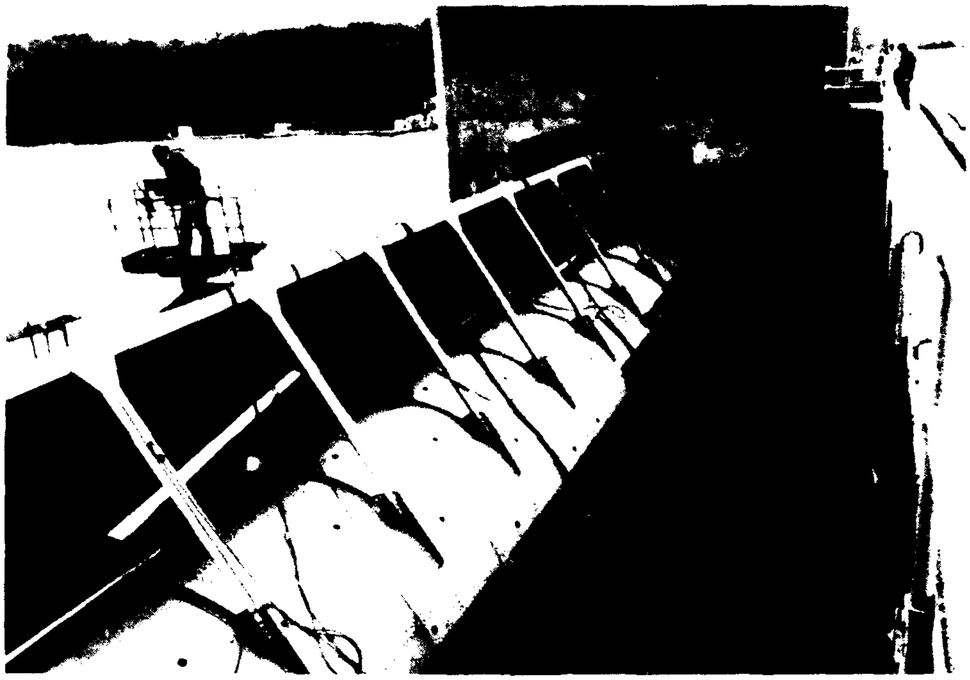

Figure 6. Roller gate with apron framing

## Loadings on spillway gates

In use, all spillway gates will be subjected to different combination of loads and forces. Commonly, the following loads and forces are present:

*a*. Dead load due to the weight of the gate.

*b*. Live load which mainly is due to hydrostatic pressure, but also hydrodynamic effects caused by waves, flow-induced vibration, temperature, wind, and ice.

*c*. Support reactions such as sill reactions, cable contact pressure, trunnion reactions, and friction forces.

*d*. Accidental forces due to impact, or undesired operating process; for example, one cable breaks or becomes slack, or debris wedges between the gate and a pier.

All gate types will be subjected to some or all of these loads, in varying degrees. Lift gates, for example, might have higher wind loads than tainter gates but will not have trunnion reactions. Ice loadings and loads from passing water warrant greater attention, the former because of possible high stresses that might be induced and the latter because of the flow-induced vibration that can be excited.

**Ice loading**. According to Engineer Manual (EM) 1110-2-2702 (USACE 1966), a lateral ice loading of 5,000 lb/ft of width should be used in the design of tainter gates. Using this criterion, the tainter gates at

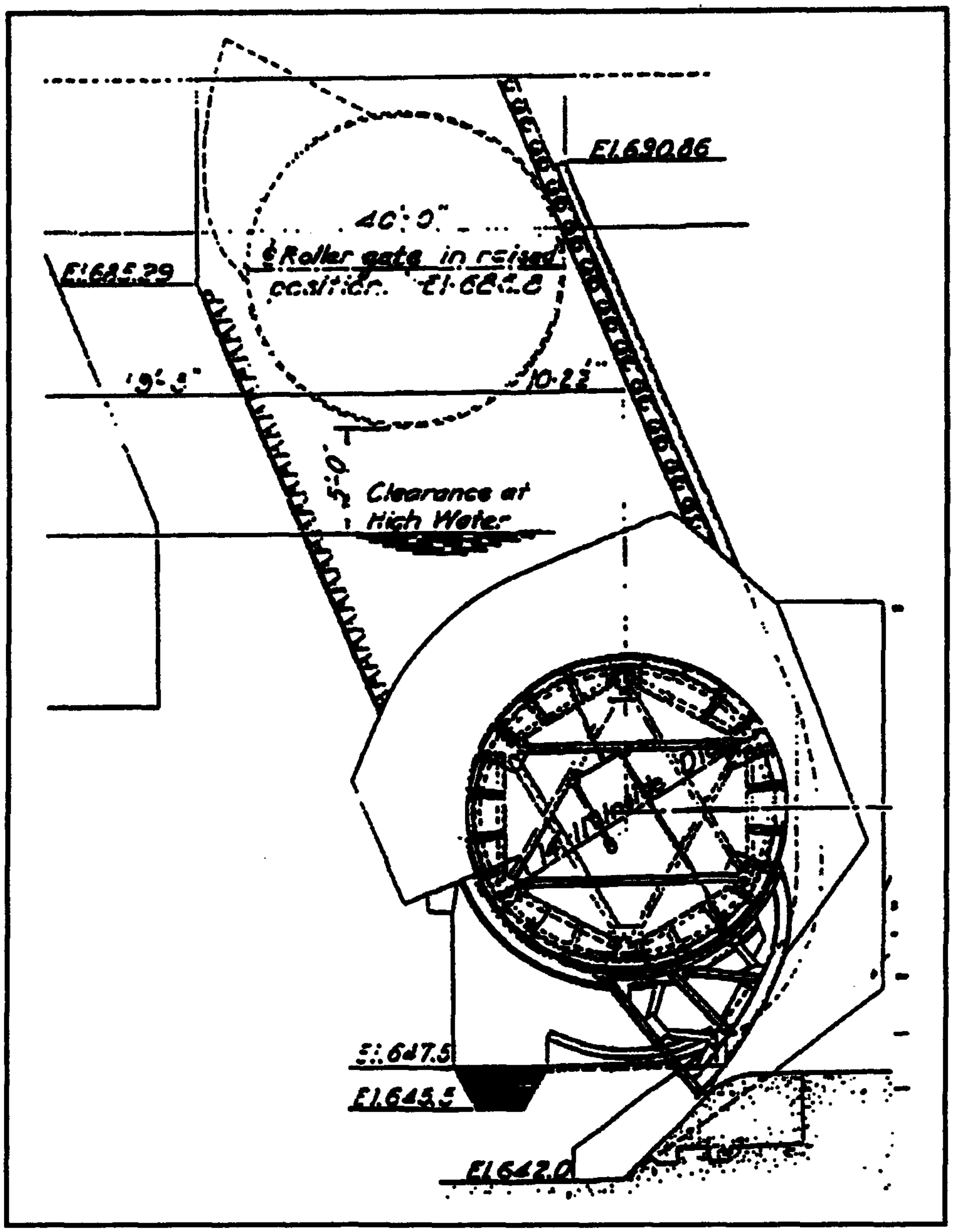


Figure 7. Roller gate cross section

Dams 4 through 10 on the Mississippi River, which were designed in the 1930's without consideration of ice loading, were reevaluated by Corps personnel for their ability to resist the ice loadings (U.S. Army Engineer District (USAED), St. Paul 1988).

Analytical studies indicated that stresses in the gate ribs, in the top girders and in the top struts, are at the yield strength of A7 steel. The stresses in the gate trunnion pins also were found to be far above the allowable design stresses, though still below the yield strength. Because the results suggested that the gates might be in distress, Corps personnel did further studies using the computer program COSMOS to analyze the distribution

of ice loads on the gates and piers. The Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) was also consulted. The studies concluded that (USAED, St. Paul 1988):

*a.* The piers resist most of the ice loading when the ice is thick and/or is fairly strong.

*b.* The design ice loading of 5,000 lb/ft of width is reasonable only when the ice is not very strong, is on the order of 1 ft thick, and yields completely around the piers.

*c.* The piers of the Mississippi River dams might cause a larger reduction in the ice forces than suggested by EM 1110-2-2702.

*d.* The 5,000-lb/ft ice loading is a guideline for design, not a specification.

**Flow-induced vibration.** In the 1960's, vibration of tainter gates occurred (USACE 1971) at several dams on the Arkansas River. Some vibration was so severe that fatigue failures occurred in a number of the structural members and welded connections of the gates. Later (USAED, St. Paul 1986), tainter gates at Lock and Dam No. 5 on the upper Mississippi River experienced vibrations similar to those observed on dams on the Arkansas River. Fatigue damage due to gate vibration was suggested as possibly being one reason leading to the brittle failure of a trunnion girder on a tainter gate at lower St. Anthony Falls Dam in St. Paul in 1981 (USAED, St. Paul 1986). Reportedly, vibration has also led to cracking in the end shields of roller gates.[1]

The Little Rock and St. Paul Districts have conducted separate investigations of this problem. They monitored tainter gates with the problem of vibration, made dynamic measurements in the field and performed a model test in the laboratory, pursued intensive analytical work and developed some modified gate seals, and worked out a new gate operating procedure to reduce the vibration.

Although any impact loads and dynamic forces such as high-rate lifting force and debris impact could cause vibration, spillway gate vibration is generally flow-induced vibration generated by water flow between the gate bottom and sill. Flow-induced vibration primarily depends on interaction between the fluid and the gate structure. The factors which are related to flow-induced vibration are the following:

*a.* The flow velocity which is related to pool differential and gate opening.

*b.* The fluid density.

[1] Personal Communication. K. D. Hokens (St. Paul District) to C. Chasten (WES), Aug. 6, 1992.

*c*. The configuration of the gate structure and the gate seal.

For spillway gates, the pool differential and the fluid density cannot be changed. What can be changed are the gate opening and the gate seal. The gate can be lifted to a position which exceeds the narrow band of gate openings that have been known to cause vibration, so no significant vibration will continue. The problems with operating gates in this way include downstream scour damage due to locally high discharge velocities and a more complicated operation.

The configuration of the gate seal is a major factor in setting up flow conditions which cause vibration. Several gate seal modifications were developed by the Little Rock District (USACE 1971). After both model and field tests, it was noted that it is necessary to provide a sharp break point for flows at all gate openings and to stiffen the bottom cantilevered portion of the gate skin plate.

From the field measurements made on Gate 24 at Lock and Dam No. 5 on the Mississippi River, it was noted that the vibration frequency was about 10.5 Hz and the relevant stress range was about 3.7 ksi on the girder and about 4.4 ksi on the strut arm (USAED, St. Paul 1986).

Although it has been realized that flow-induced vibration can usually be avoided by adjusting the operating procedure and employing proper gate seals, the problem does occur and is of concern. Further study of this phenomenon is still necessary.

## Gate Materials Standards

### Reference drawings

Representative drawings of spillway gates were requested from the U.S. Army Engineer Waterways Experiment Station (WES) for review of both the design and fabrication aspects of various gate styles. WES furnished drawings[1,2] of gates at Mississippi River Lock and Dams Nos. 4 and 25. Lock and Dam No. 4 drawings included both tainter and roller gates; Lock and Dam No. 25 drawings included only tainter gates. Both sets of drawings were made in 1933-1937. Also, personnel at the

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1 U.S. Army Corps of Engineers Upper Mississippi Valley Division. (1937). "Mississippi River Lock & Dam No. 25 Dam 60 ft x 25 ft Tainter Gate," Drawings M-L25-48/0A to 8.1.

2 U.S. Army Corps of Engineers Drawings. (1933-1937). "Mississippi River Lock & Dam No. 4," (a) General: M-L4-0/2-FS and 40/1 to 3-FS; (b) Tainter gates: 40/55- and 56-FS and -48/1- to 15-FS; (c) Roller gates: 47/A- and B- and 1- to 22-FS.

Tuscaloosa office of the Mobile District furnished drawings[1,2] of a vertical lift gate at Lock & Dam No. 17 (currently named John Hollis Bankhead Lock & Dam) on the Black Warrior River. These latter drawings were made in 1935.

The drawings of the Mississippi River gates indicated very little about the steels used to fabricate the gates. "Structural steel" was the common notation and apparently included structural steel plates, shapes (such as angles and channels), and rivets. The drawings of the Black Warrior River gates used a different notation. Structural members were either "carbon steel" or "silicon steel," depending on the size of the gate and application of the member. Higher strength silicon steel (21,000 psi allowable stress in tension and bending[2]) seemed to have been used for main structural plates and angles in 52-ft-wide gates whereas carbon steel (14,000 psi allowable stress[1]) was apparently used for stiffeners and other nonstructural elements on the 52-ft-wide gates and all components of the smaller 24-ft-wide gates. The rivet steel was identified on the drawings as being carbon steel in all cases. No specific references to ASTM designations were found on these early drawings.

## Structural steel standards

Steel standards for the period when many riveted spillway gates were constructed are of interest from both a structural evaluation standpoint and a repair and maintenance standpoint. In structural evaluations performed today, the characteristics of corrosion resistance, fracture resistance, crack propagation rate, and stability of properties with seasonal temperature changes are considered important parameters. However, at the time the gates were constructed, these properties probably were not determined or even much considered. Moreover, when considering repair and maintenance to steel structures today, welding almost certainly will be considered, even for riveted structures. Therefore, it is critical to be aware of the of the properties and the weldability of steel in older, riveted structures. Therefore, the following brief discussion of earlier structural steels is provided.

**In the 1930's.** At the time that many riveted gates were designed and built in the mid-1930's, "structural steel" could have been supplied as either American Society for Testing and Materials (ASTM) A7 or ASTM A9 steel (American Institute of Steel Construction (AISC) 1953). The A7 steel was generally regarded at the time as a "steel for bridges" (ASTM 1933a) whereas A9 steel was a "steel for buildings" (ASTM 1933b). The primary differences between the two were that A7 steel had a lower maximum allowable phosphorus content than A9 steel and, in contrast to A9

1 U.S. Army Corps of Engineers. (1935). "Lock & Dam No. 17, Black Warrior River, Ala., Crest Gates," Details of 52-ft Gate, Sheets No. 1 to 3. Mobile, AL.

2 *Ibid.* Design Sheet No. 3, Gates.

steel, had a limit on sulfur content. A7 steel also was restricted to open-hearth or electric furnace production, and excluded the older acid-bessemer production. These compositional and production restrictions suggest that A7 bridge steel was recognized as the premium steel of the two.

For a brief period (1932-33), "structural steel" also could have been supplied as ASTM A140 steel, which was a tentative replacement for both A7 and A9 steels (AISC 1953).

"Silicon steel" as identified on the Black Warrior River drawings was probably ASTM A94 structural silicon steel (ASTM 1925). This was a high-strength steel with a specified minimum silicon content that attained its high strength (minimum yield point of 45,000 psi and tensile strength of 80,000 to 95,000 psi) through a high level of carbon (0.44 percent maximum). It also had limits on its phosphorus and sulfur contents.

An important characteristic of the early steels, regardless of whether they were A7, A9, A140, or A94 silicon steel, is that they either had no specified level or a high level of carbon in their composition. Consequently, the carbon level was either not rigorously controlled or was moderately high, with the result that the steels probably only had and have poor to fair weldability. The specification for A94 structural silicon steel specifically limits welding and specifies a preheat condition when welding must be done. Of course, the steels were being used for riveted structures, so weldability was not then a concern to designers. But it needs to be considered for weld repairs or maintenance contemplated today.

**Up to date.** In 1939, A7 and A9 were consolidated into a single specification, A7 steel for bridges and buildings (ASTM 1939), which then became the single specification for "structural steel." In 1954 a new "structural steel for welding," A373 steel, was introduced (ASTM 1958). Both A7 and A373 steels were consolidated in 1965 into the one specification, A36 steel (ASTM 1960), which is the basic structural steel today, and is used for both welded and bolted applications.

**Allowable and yield stresses.** During the same period that A7 steel was evolving, AISC changed its basic allowable working stress for structural steel only once and raised it in 1936 from 18,000 psi to 20,000 psi (AISC 1953). The ASTM requirement for minimum yield point during this period was generally 0.5 × tensile strength or not less than 30,000 psi; in 1933, the minimum of 30,000 psi was raised to 33,000 psi for plate and shape products. When A373 steel was introduced, that steel had a minimum yield point of 32,000 psi, suggesting that to improve weldability at that time, some sacrifice in strength was necessary. Only when A36 steel was introduced in 1960 in a tentative specification (ASTM 1960), did the minimum yield point for structural steel plates and shapes increase to 36,000 psi. By that time, weldability and welding practices for structural steel had markedly improved and standardized.

## Rivet steel standards

The spillway gate drawings that were reviewed for this report did not specify rivets by steel grade, only as "structural steel," "carbon steel," or as "rivets." However, the allowable shear stress for power-driven rivets was occasionally identified as 12,000 psi, and the allowable bearing stress as 24,000 psi.

Until 1932, "rivet steel" was included in the ASTM A7 and A9 specifications, but with lower yield and tensile strengths than "structural steel" (AISC 1953). However, in 1932, ASTM A141 was issued as a tentative specification for "structural rivet steel," with somewhat more enhanced strength requirements than earlier (ASTM 1932). More restrictive diameter tolerances were included in a 1936 tentative revision. Until 1949, rivet yield strength was specified as 0.5 × tensile strength or not less than 28,000 psi. In 1949, the yield strength for A141 rivet steel was changed to 28,000 psi minimum (AISC 1953). In 1960, A141 rivet steel was incorporated into the new tentative A36 steel specification (ASTM 1960).

In 1936, a new tentative specification, ASTM A195, was issued for "high-strength structural rivet steel," for rivets produced from structural silicon steel (ASTM 1936). As opposed to A141 rivet steel, A195 rivet steel had carbon, manganese, silicon, and copper requirements. In addition, A195 rivet steel yield strength was specified as 0.5 × tensile strength or not less than 38,000 psi. A195 steel rivets were to be used with A94 structural silicon steel, although the Black Warrior River drawings seemingly would suggest that A141 steel rivets continued to be used.

In 1964, a new specification, ASTM A502, was published for "steel structural rivets," and superseded ASTM A141 and A195. The later version (ASTM 1983) of this specification covers three grades of steel rivets: (a) general purpose carbon steel rivets, (b) carbon-manganese steel rivets for use with high-strength carbon and high-strength, low-alloy steels, and (c) rivets comparable to ASTM A588 weathering steel. The later specification includes hardness requirements but not tensile and yield strength requirements.

## Weldability of earlier steels

A very good reference that discusses the weldability of steels, including steels that have limited weldability, is the monograph "Weldability of Steels" published by the Welding Research Council. Now in its fourth edition (Stout et al. 1987), the monograph has chapters on the properties of steel related to weldability, factors affecting weldability in fabrication, and the weldability of different steels. Although the fourth edition does not specifically mention the earlier A7, A9, and A94 steels, it does provide suggested (as of 1987) practices that are generally required for sound welding for a variety of steel compositions and steel thicknesses,

including A36 steel. These suggested practices include minimum preheat and interpass temperatures, postweld heat treatments, and recommendations for weld peening.

For comparison, reference can also be made to the first edition of the monograph (Stout and Doty 1953) which includes suggested (as of 1953) welding practices for A7 steel meeting the tentative specification A7-50T. However, even the first edition does not include data for A9 or A94 steels.

A copy of the suggested (1953) practices for A7 steel and a copy of the suggested (1987) practices for A36 steel are included in Table 1. For thicknesses up to 1 in., the normal case in spillway gates, a comparison of the recommended practices in Table 1 suggests that for carbon levels of 0.25 percent or less, no special welding requirements are needed for either A7 or A36 steels. However, as the carbon level increases, more stringent practices are needed. Because A7 steel did not have a specified carbon level, repair and maintenance welding should be conducted favoring the more stringent practices.

Therefore, a conservative practice is recommended when repair and maintenance welding on riveted spillway gates must be performed—when necessary. Use the practices for A7 steel in Table 1, with the assumption that the carbon level is between 0.26 and 0.30 percent.

## Table 1
## Suggested Practices for Sound Welding with A7 and A36 Steels (Stout and Doty 1953, Stout et al. 1967)

### A7 Steel

**Conditions Requiring No Preheating, Postheating, or Special Electrodes**

| Steel Specification | Conditions for Which No Special Precautions Are Required: Carbon Range, % | Conditions for Which No Special Precautions Are Required: Thickness Range, in. | Remarks | Grade or Quality | Specification Requirements (Abridged): Composition: C | Mn | Si | Ni | Cr | Mo | Other | Yield Point psi | Tensile Properties: Tensile Strength psi | Tensile Properties: Elongation % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ASTM A7-58T Steel for bridges and buildings | Up to 0.25, incl | Up to 1, incl | Over 1 in., see Table II | ... | (Not specified) | (Not specified) | (Not specified) | ... | ... | ... | 0.20 min. Cu when specified | 33,000 min. | 60,000-72,000 | 21 in 8 inches (min.) |
| | 0.26-0.30, incl | Up to 1/2, incl | Over 1/2 in., see Table II | | | | | | | | | | | |
| | | | Over 0.30 carbon, see Table II | | | | | | | | | | | |

**Table II. Conditions Requiring Some Control Over Heat Input and Requiring Low Hydrogen Electrodes or Preheat and Generally Postheating**

| Carbon Range % | Thickness Range in. | Recommended Arc Welding Conditions General Notes: Electrodes should be of suitable composition when alloy steels are welded. Welding conditions are not given for materials over 4 inches thick. |
|---|---|---|
| Up to 0.25 incl | Over 1-2, incl | Condition A or B |
| | Over 2-4, incl | Condition C |
| 0.26-0.30 incl | Over 1/2-1, incl | Condition A or B |
| | Over 1-2, incl | Condition B or C |
| | Over 2-4, incl | See Table III |
| 0.31-0.35 incl | Up to 1/2, incl | Condition A or B |
| | Over 1/2-1, incl | Condition B or C |
| | Over 1-4, incl | See Table III |

Condition A = 100°F minimum preheat and interpass temperature. 1100-1250°F stress relief optional.

Condition B = No welding below 10°F, EXX15 or EXX16 electrode. 1100-1250°F stress relief optional.

Condition C = 200°F minimum preheat and interpass temperature. 1100-1250°F stress relief optional.

**Table III. Conditions Requiring Preheat, Special Welding Techniques, and Postheating and/or Peening**

| Carbon Range, % | Thickness Range, in. | Recommended Arc Welding Conditions General Notes: Electrodes should be of suitable composition when alloy steels are welded. Welding conditions are not given for materials over 4 inches thick. |
|---|---|---|
| 0.26-0.30 incl | Over 2-4, incl | Condition J |
| 0.31-0.35 incl | Over 1-2, incl | Condition J |
| | Over 2-4, incl | Condition K |

Condition J = 100°F minimum preheat and interpass temperature with EXX15 or EXX16 electrode or 300°F preheat with other than EXX16 electrode, 1100-1250°F stress relief optional, peening may be necessary for thicknesses over 1 inch.

Condition K = 200°F minimum preheat and interpass temperature with EXX15 or EXX16 electrode or 300°F preheat with other than EXX15 or EXX16, 1100-1250°F stress relief optional, peening may be necessary for thicknesses over 1 inch.

### A36 Steel

| Steel Specification | Suggested Welding Conditions: Carbon Range % | Thickness Range in. | Minimum Preheat and Interpass Temperature, °F: Low-Hydrogen | Minimum Preheat and Interpass Temperature, °F: Other Than Low-Hydrogen | Post-Weld Heat-Treatment Range, °F | Peening May Be Necessary | Specification Requirements (Abridged): Class, Grade or Quality | Composition: C | Mn | Si | Ni | Cr | Mo | Other | Tensile Properties: Yield Point psi | Tensile Strength psi | Elongation % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ASTM A36-61 Structural Steel | Up to 0.25 incl | Up to 1, incl | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | — | — | 0.25-0.29 Max. depending on thickness & mill product | 0.80-1.20 for plates over 3/4 in. 0.60-0.90 for bars over 3/4 in. (not specified for shapes or for bars or plates up to 3/4 in.) | 0.15-0.40 (not specified for shapes or bars or for plates up to 1-1/2 in.) | — | — | — | 0.20 Min. Cu when specified | 36,000 Min. | 58,000-80,000 | 20 Min. in 8 inches |
| | | Over 1 to 2, incl | 50 | 200 | Optional 1100/1250 | — | | | | | | | | | | | |
| | | Over 2 to 4, incl | 150 | 300 | Optional 1100/1250 | Yes | | | | | | | | | | | |
| | 0.26-0.29 incl | Up to 1/2, incl | Ambient, Above 10°F | Ambient, Above 10°F | Optional 1100/1250 | — | | | | | | | | | | | |
| | | Over 1/2 to 1, incl | 50 | 200 | Optional 1100/1250 | — | | | | | | | | | | | |
| | | Over 1 to 2, incl | 150 | 300 | Optional 1100/1250 | Yes | | | | | | | | | | | |
| | | Over 2 to 4, incl | 200 | 300 | Optional 1100/1250 | Yes | | | | | | | | | | | |

Note: For welding and post-weld heat-treatment requirements for boilers or pressure vessels fabricated from this material refer to appropriate section of ASME Boiler & Pressure Vessel Code.

# 3 Task 2 - Site Review of Gates

To observe the operation of the various types of riveted spillway gates and to identify critical structural areas and common problems, visits were made to four gate installations where observations were made of riveted vertical lift, tainter, and roller gates. The information obtained was also intended to serve as background for case studies for an evaluation guide.

## Introduction

The locations selected by the Corps of Engineers for these inspection visits included the John Hollis Bankhead Lock & Dam on the Black Warrior River in Alabama and Lock and Dam Nos. 2, 5, and 9 along the Upper Mississippi River.

The John Hollis Bankhead Lock and Dam (Figure 8) is located in the Corps' Mobile District, approximately 40 miles northeast of Tuscaloosa, AL, and was visited by ATLSS personnel and Corps representative Mr. L.E. Bridges (Mobile District - Tuscaloosa Office) on April 23, 1991.[1] The dam was originally built in 1915 and was modified in 1936 to increase the pool elevation by installing 22 fixed-wheel, single-section vertical lift spillway gates of riveted construction. Currently, 21 of the spillway gates are the original riveted structures, and the 22nd is a welded gate installed in 1991. The reasons for this gate replacement are explained below. All gates were reported to be operational and to maintain a maximum pool differential of 69 ft at the dam with no tailwater conditions. The Holt Lake Lock and Dam, which is located downstream of Bankhead Dam, was also visited. Because the spillway gates at this facility are of welded construction, a discussion of the findings will not be included in this report.

1 M. R. Karczinski, report of trip to Tuscaloosa office, memo to project file, May 19, 1992.

Figure 8. John Hollis Bankhead Lock and Dam, Black Warrior River, AL

Lock and Dam Nos. 2, 5, and 9 are all located on the Mississippi River (St. Paul District) and were visited on May 27-28, 1992 by a team of ATLSS and Corps personnel.[1] Dam No. 2 is located at Hastings, MN (Figure 9), and was originally built in the 1920's to maintain a pool differential of approximately 12 ft. The dam consists of 19 riveted tainter gates constructed in a unique three-dimensional space truss configuration. Lock and Dam No. 5 near Winona, MN (Figure 10), was built from 1933-1935 and consists of 6 riveted roller gates and 28 riveted tainter gates. A pool differential of approximately 8 ft is maintained at the dam. Finally, Dam No. 9 near Lynxville, WI (Figure 11), was also inspected. This structure consists of five riveted roller gates and eight riveted tainter gates which were built from 1934-1938 and are used to maintain a pool differential of approximately 8 ft. The spillway gates at all three locations were reported to be in operating condition. In fact, many of the gates are operated several times each week to control the river flow. Because high tailwater conditions exist at these sites, the gates tend to accumulate a significant amount of debris. No routine maintenance program is followed to remove debris or touch-up painted areas. A discussion of the structural steel used in construction of the spillway gates was presented in Chapter 2.

Observations of the riveted lift, tainter, and roller type spillway gates visited at each site are summarized below.

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1 M. R. Maczinski, report of trip to St. Paul District office, memo to project file, June 17, 1992.

Figure 9. Lock and Dam No. 2, Mississippi River, Hastings, MN

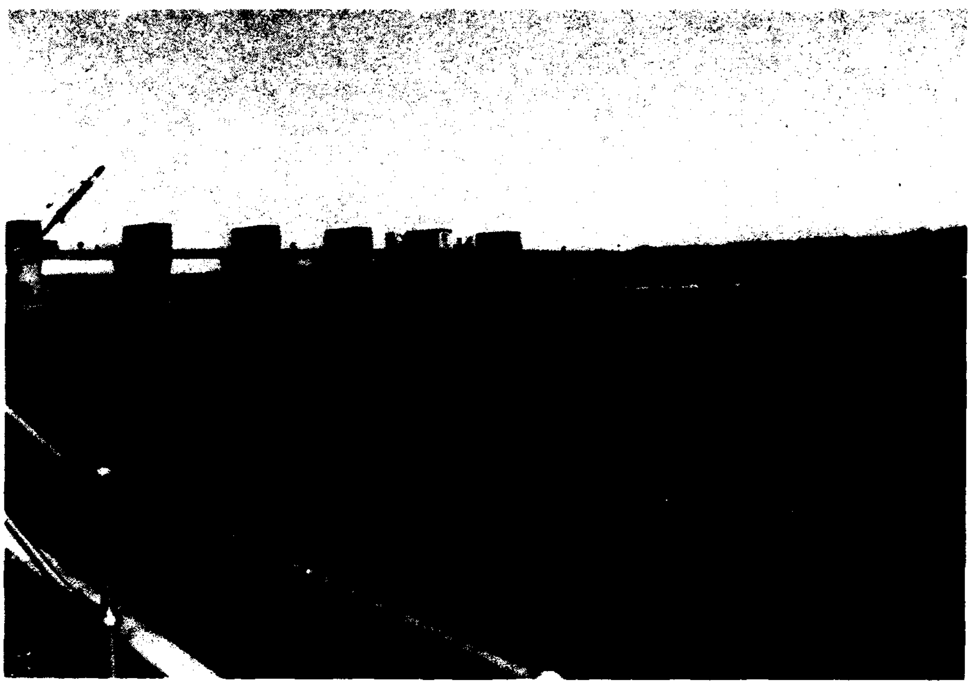

Figure 10. Lock and Dam No. 5, Mississippi River, Winona, MN

Figure 11. Lock and Dam No. 9, Mississippi River, Lynxville, WI

## Lift Gates

At Bankhead Lock and Dam, the built-up riveted gates are 52 ft, 3-3/4-in. long; 13 ft, 6-in. high; and 2 ft, 7-3/4-in. in depth (Figure 12). Five cover-plated and stiffened girders are the main load and carry members of the gate and support a 3/8-in.-thick skin plate. A 3-in.-thick steel casting, which acts as a base seal, is bolted to the bottom girder along the entire length of the gate. A copy of a portion of the framing plan is attached. All structural elements (beam web, flanges, etc.) of the gate are specified as "silicon" steel with an allowable tensile stress of 21 ksi. Stiffeners and other nonstructural elements are specified as "carbon" steel with an allowable tensile stress of 14 ksi.

A thorough inspection was made of the riveted lift gate which was removed from the dam in 1991 and replaced by the welded gate. When inspected, this gate was lying down in a horizontal position rather than the normal operating vertical position. No sign of structural distress (i.e., fatigue cracks, fractured or buckled members) or repaired members were observed, nor were any structural problems reported by Mr. Bridges. A moderate amount of corrosion was evident on the top side of each girder web due to the buildup of debris. As shown in Figure 13, more significant corrosion was seen at the lower corners of the lift gate with some rivet heads suffering 100 percent section loss. The cast steel base seal was also corroded and irregularly eroded from the 56 years of service. This eroded base seal did not make a watertight fit and was one of the reasons given for replacing the gate. Another reason cited was the corrosion of the lower corners of the gate; however, the most compelling reason for

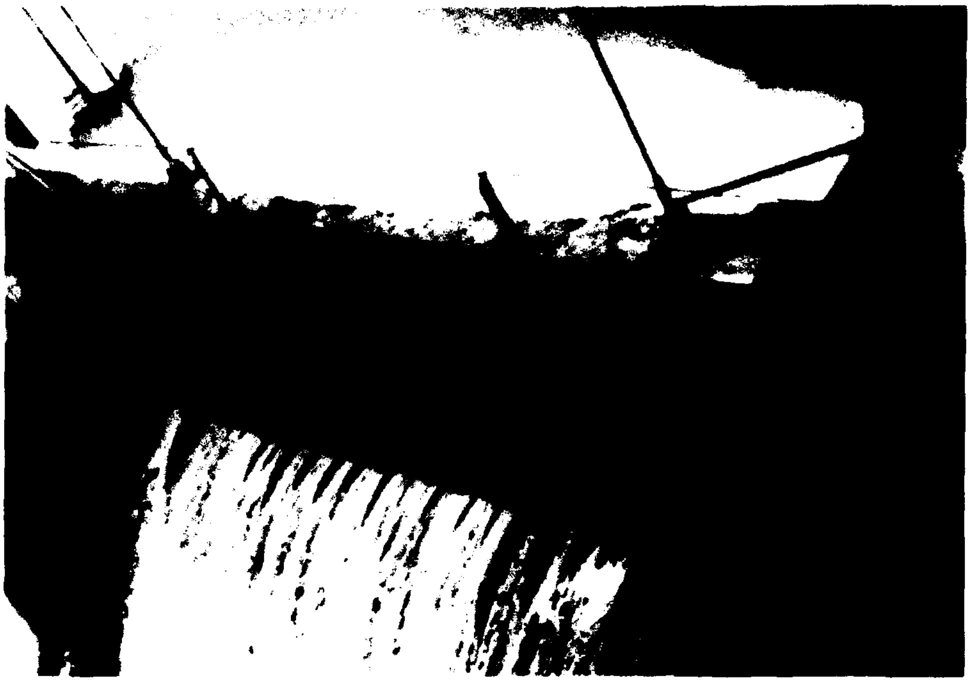

Figure 12. Riveted vertical-lift gate at Bankhead Dam

Figure 13. Heavy corrosion in lower corner of lift gate at Bankhead Dam

replacing the riveted gate was mechanical failure of the bearings in the two reaction and guide wheels along each side of the gate. Mr. Bridges reported that, as a preventative measure, the 21 remaining riveted lift gates will be replaced with welded structures with new reaction and guide wheels as funds become available.

An Alabama Power Company hydroelectric generating plant is located at the dam; therefore, water conservation is an important consideration in gate operations. It was reported that the gates are only opened 3 to 4 times each year during very severe rain storms. During these periods the gates are usually left open approximately 3 to 4 days.

Typically, one general inspection of a gate structure is made annually as debris is cleaned from the gate and corroded areas are painted. According to Mr. Bridges, beyond this cleaning and inspection, no other program is followed for inspecting the gates, and the lockmen are solely responsible for reporting any unusual behavior in the performance of the gates.

## Tainter Gates

At Lock and Dam No. 2 each gate is 30 ft wide, 20 ft high, and 28 ft in radius from the center of the trunnion bearing to the skin plate and is constructed as a three-dimensional space truss as shown in Figure 14. This structural configuration is unique for tainter gates and consists of a series of 11 frames along the 30 ft width to carry the loads from the skin plate.

Figure 14. Truss-framed tainter gate at Lock and Dam No. 2

A major reconstruction program was completed at the dam in 1989. Rehabilitation work on the spillway gates included strengthening/replacing some of the lighter riveted truss members with heavier bolted members to meet current ice load provisions, removing and replacing corroded or loose rivets, and painting the steel framework. Several gusset connection plates now include a combination of rivets and bolts. In addition, four gates (Nos. 8 to 11) were modified to include electric heaters on the skin plate and side seals.

No sign of structural distress was visible and only a moderate amount of pitting corrosion was evident on the top surface of gusset plates and chord members and along the skin plate at the water line. One minor concern was the attachment of small brackets and angles to the riveted members with tack welds which are susceptible to fatigue cracking. It was reported that these attachments are the remains of an enclosure over the gate structure and welded ladders used with these enclosures. These enclosures were reportedly removed because too much moisture was being retained which caused corrosion.

At Lock and Dam No. 5, the gates are 35 ft wide, 15 ft high, and 25 ft in radius from the trunnion pin to the face of the skin plate (Figure 15). The structure is framed similar to the design and detail provisions for tainter gates in EM 1110-2-2702 (USACE 1966) with a 3/8-in. skin plate, C12 by 25 vertical ribs, two W30 by 118 horizontal girders, and W18 by 80 strut arm frames. All connections are riveted except for the use of bolts at the strut arm-trunnion block detail. A plate is also placed on the gates to divert water and ice off the web of the top girder. On four submersible gates (Nos. 19, 20, 33, and 34), this diverter plate extends from the top

Figure 15. Tainter gate at Lock and Dam No. 5

girder to the top of the gate. All nonsubmersible gates use Type J side and bottom seal details which have been reported (USACE 1971, 1986) to be prone to vibration problems. Corrosion was seen on some of the rivet heads and along the top surface of the web on the upper horizontal girder under the diversion plate.

Web and flange buckling on the strut arms adjacent to the knee brace intersection from the upper horizontal girder was visible on several gates and is most severe on gate No. 24. As reported in Corps documents, this damage is believed to be a result of excessive ice loads on the structure (Tante 1990, Hokens 1989[1]).

With the assistance of lock personnel, Gate No. 23 was fully closed and then reopened approximately 0.1 ft when vibration began normal to the face of the gate. By rough measurement, the vibration frequency was estimated at 5 to 10 Hz. The amplitude of the vibration was maximum at midspan of the gate and was sufficient to create an audible noise and make ripples in the backwater as shown in Figure 16. Although the vibration damped out towards the strut arms, it was still noticeable at the trunnion pins. It was reported that the gates would normally not be set in a position which starts vibrating. No fatigue cracks were detected on the structure. Although the gate is of riveted construction, groove welding was used to water-seal the gaps between adjacent skin plates, and

[1] K. Hokens, Tainter gate strut arm bending at Lock and Dam No. 5, memorandum for record (with St. Paul District computation sheets), July 19, 1989.

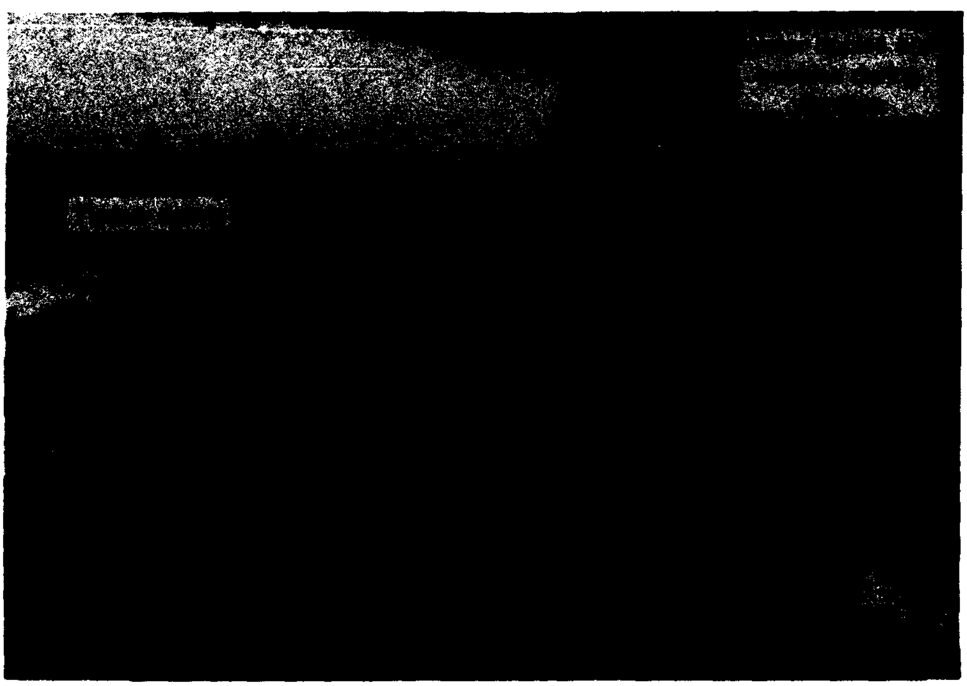

Figure 16. Effects of vibration at gate No. 23 on Lock and Dam No. 5

tack-weld attachments were made to the diversion plate on alternating rib channels.

At gate No. 25, one chain hoist was out of its guide on the skin plate. This condition may cause an eccentric hoist load on the gate.

At Lock and Dam No. 9, the gates are 35 ft wide, 15 ft high, and 25 ft in radius from the trunnion pin to the face of the skin plate. With the exception of the strut arms being increased (to W18 by 96's), the structural framing and member sizes are similar to the tainter gates at Dam No. 5. Two of the gates are detailed as submersible units similar to those at Dam No. 5. A photo of the submersible unit at Gate No. 13 is shown in Figure 17.

The tainter gates were repainted in 1992 and appear in excellent condition with no evidence of structural distress. A small amount of pitting corrosion was visible on the skin plate and along the top surface of the web on the upper girder. This corrosion of the girder web appears to be caused by the ponding of water below the drain holes.

Bicycle chain hoists are used on all gates at Lock and Dam No. 9 rather than the chain link hoists used at Lock and Dam Nos. 2 and 5.

Figure 17. Submersible tainter gate at Lock and Dam No. 5

## Roller Gates

At Lock and Dam No. 5, the gates are 60 ft wide, 15 ft in diameter, and 20 ft in height when the roller apron is included. No structural distress, significant corrosion, or paint blistering was visible. The rivet pattern on these gates has a more uniform pitch and fewer transverse rows of rivets than the roller gates at Dam No. 9.

At Lock and Dam No. 9, the gates shown in Figure 18 are 80 ft wide, 15 ft in diameter, and 20 ft in height when the roller apron is included. No signs of structural distress were visible; however, the exposed surfaces of the roller cylinder have developed excessive paint blistering. Pitting corrosion and a small amount of rivet head deterioration were also evident on both the skin and apron plates.

A painting contract is currently under way to restore the exterior of the roller gates and replace deteriorated and worn seals and seal plates.

## Summary of Findings

In general, all of the gates inspected were operable and showed no significant structural distress. However, corrosion was observed during each gate inspection. While significant corrosion damage was observed on the out-of-service lift gates at Bankhead Lock and Dam, pitting corrosion and/or blistering paint were visible on all in-service gate structures.

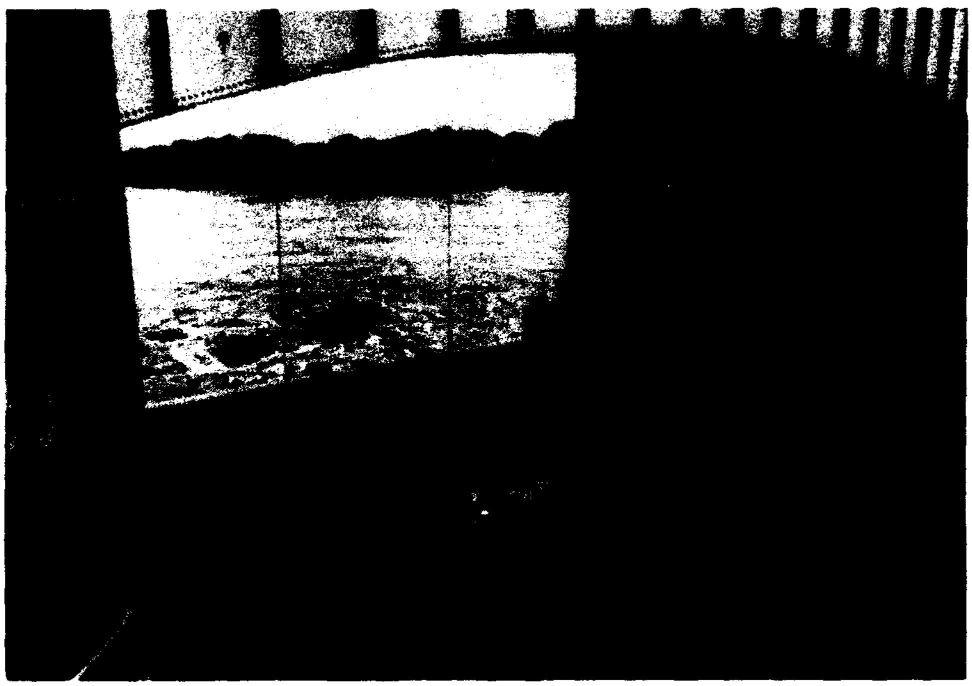

Figure 18. Roller gate at Lock and Dam No. 9

**In addition to the effect of corrosion on structural integrity, the mechanical systems can also be adversely affected. For example, as observed at Bankhead Lock and Dam, in lift gates the performance reliability of submerged mechanical systems is an important consideration. Through a regularly scheduled painting and maintenance program the effects of corrosion can be controlled.**

# 4 Task 3 - Environmental Effects on Gates

As described in Chapter 3, the onsite inspections of gates in the Mobile and St. Paul Districts indicated that corrosion occurs on spillway gates, on both structural and auxiliary mechanical components. In fact, it was noted that corrosion of the roller guides on one vertical lift gate provided a strong impetus to replace the total gate.

This chapter describes the damaging structural effects of corrosion, the types of corrosion that were observed or can be expected to affect riveted spillway gates and how to recognize them, and the parameters influencing the rate of corrosion. Inspection techniques to assess the severity of corrosion are discussed in Chapter 6.

## Damaging Structural Effects of Corrosion

Corrosion is an important parameter in structural evaluations because it can seriously weaken a structure or impair its operation. Corrosion has in fact caused notable catastrophic failures in bridges.

Three major degrading effects of corrosion on structural members are: (a) a loss of cross section, (b) a loss of strength for several limit states, and (c) a buildup of corrosion products at connection details.

A loss of cross section is critical because it leads to an increase in the nominal stress level even though there is no change in the imposed loading. Moreover, there is also a loss of dimensional properties, such as moment of inertia, which can lead to increased distortion under the load. Typically, designers and specifications have accounted for a loss of cross section by adding a corrosion allowance to the design thickness or size.

A loss of nominal strength will result from a loss of cross section. However, the loss of strength for different limit states is not uniform. Depending on its location, corrosion may affect bending strength more than

shear strength or vice versa, depending on where it is concentrated on a flexural member. Also, localized corrosion of a structural member can reduce its local buckling strength. A loss of fatigue strength also may occur because of pits and notches resulting from corrosion. These pits and notches are stress risers. In areas of high cyclic stress, fatigue cracks, oriented perpendicular to the alternating applied tensile stress, may form at the pits and notches resulting from the corrosion. These cracks will also cause failure of the paint film and will result in a visible rust line.

In areas of high static tensile stress, a loss of strength also may occur due to "stress corrosion" (if the structural material is susceptible to stress corrosion). However, this is unlikely with material such as A7 steel in a freshwater environment at ambient temperature.

A buildup of corrosion products can be particularly damaging at connection details. This can lead to extremely high pin friction in a tainter gate trunnion and may ultimately prevent rotation and gate operation. A similar buildup of corrosion product at the axles of lift gate wheels could cause those wheels to "freeze" and lead to an excessive hoist load. At connections between adjacent plates or angles, a buildup of rust could cause prying in the riveted connections which can add excess tension force to the rivet and cause loads to be transferred with eccentricity and unwanted bending at the connections.

In order to prevent long-term structural damage, corrosion must be controlled through a program of inspection, evaluation, and maintenance. This general conclusion applies for all spillway gates, not just riveted ones.

## Types and Identification of Corrosion Affecting Gates

During the onsite inspections of gates, the most common characteristics of corrosion observed were: (a) blistering and loss of the paint (Figure 19), and (b) discoloration from corrosion, either localized (Figure 20), or widespread (Figures 19 and 21). Both are indicative of a failure of the paint system. (The forms of corrosion are discussed in detail in ASM International (1987) and Slater (1987).)

Associated with these characteristics were probably three primary types of corrosion: crevice corrosion, pitting corrosion, and galvanic corrosion.

However, in a more general sense, the gates—based on their designs, the steels (ASTM A7 or A9) used in their construction, and the onsite inspections—could possibly be degraded by several types of corrosion. These are:

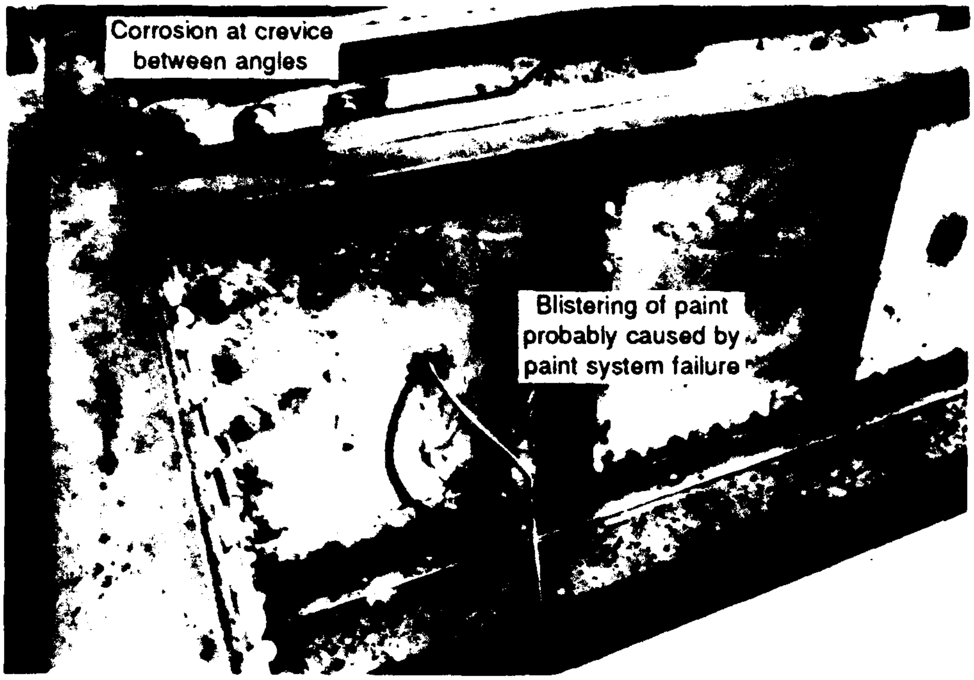

Figure 19. Vertical lift gate at Bankhead Lock and Dam with paint blistering and corrosion

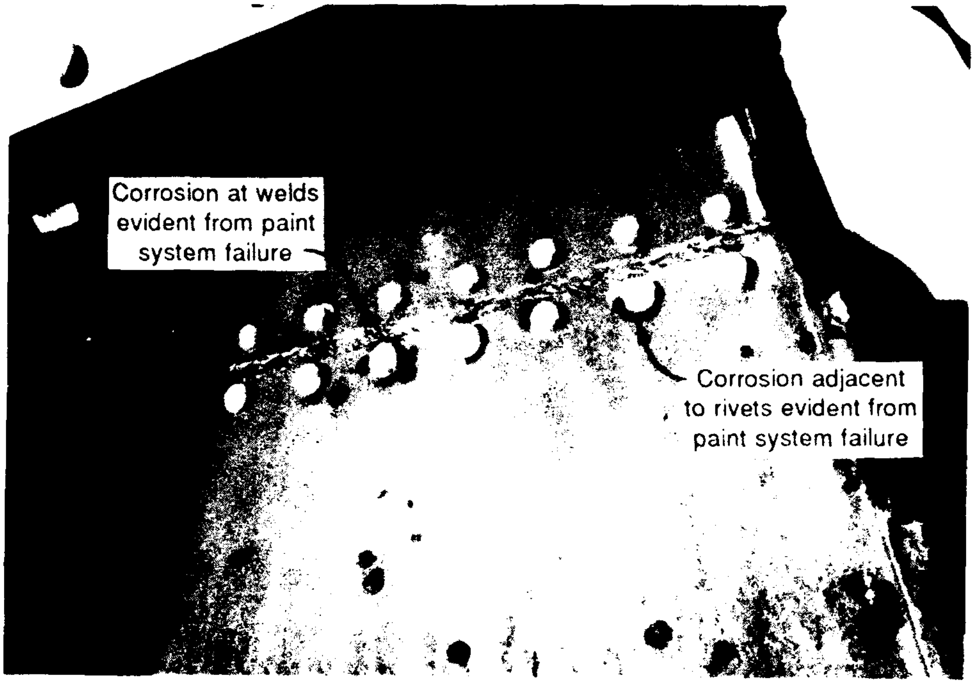

Figure 20. Tainter gate at Mississippi Lock and Dam No. 5 with seal weld and localized corrosion

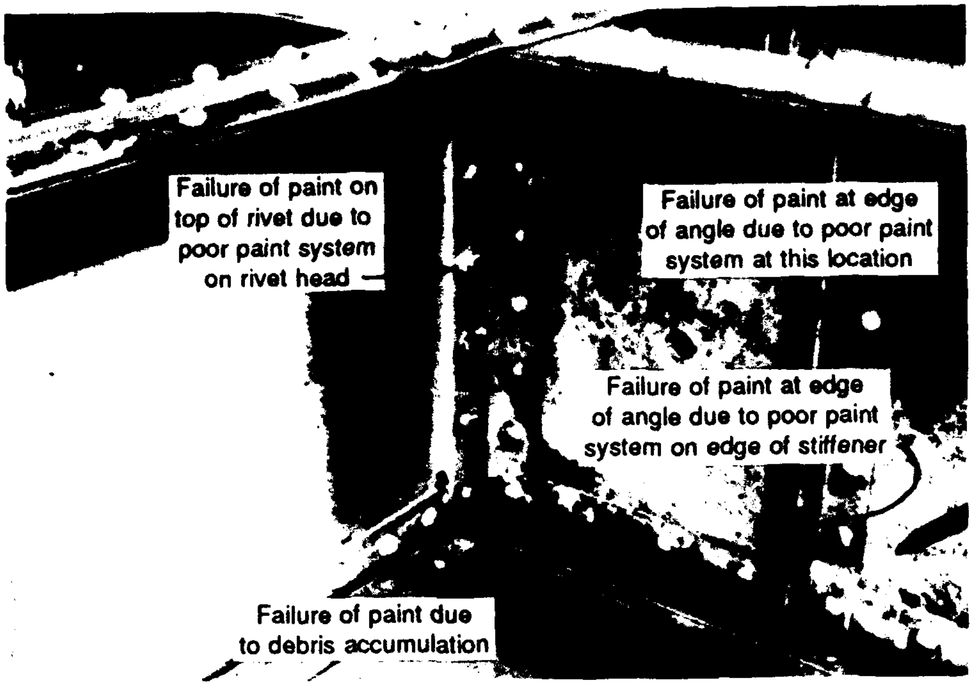


Figure 21. Vertical lift gate at Bankhead Lock and Dam with crevice corrosion, corrosion at edges, and corrosion on rivet heads

*a*. General atmospheric corrosion.

*b*. Localized corrosion.

(1) Crevice corrosion.

(2) Pitting corrosion.

(3) Galvanic corrosion.

(4) Stray-current corrosion.

(5) Filiform corrosion.

*c*. Mechanically assisted corrosion.

(1) Erosion corrosion.

(2) Cavitation corrosion.

(3) Fretting corrosion

## General atmospheric corrosion

General atmospheric corrosion is defined as corrosive attack which results in slow, relatively uniform thinning. It is expected to occur in the ambient environment of spillway gate structures, but is not likely to cause significant structural degradation since the corrosion is spread over a wide area.

## Localized corrosion

Localized corrosion is the type of corrosion most likely to affect riveted gate structures. And, because it occurs at specific sites and with faster rates than general corrosion, it warrants more concern. All five of the types of localized corrosion are possible on gate structures.

**Crevice corrosion.** Crevice corrosion occurs in narrow openings between two contact surfaces, a condition prevalent with riveted gates, making crevice corrosion a strong concern. Typically, crevices occur between adjoining plates or angles (Figures 19 and 21), or between a rivet head and the adjoining plate or angle (Figure 19). It can also occur between a steel component and a nonmetal one (under the seals, a paint layer, or debris, sand or silt, or biological organisms caught on the gate members). It can lead to blistering and failure of the paint system.

**Pitting corrosion.** Pitting corrosion occurs on bare metal surfaces as well as under paint films; it is characterized by small cavities penetrating into the surface with little extension along the surface. If pitting occurs under paint, it can result in the formation of a blister and failure of the paint system. Although closeup photographs were not obtained, pitting was observed on the roller gate that was undergoing repainting during the onsite inspection at Lock and Dam No. 9 (Figure 6).[1]

**Galvanic corrosion.** Galvanic corrosion can occur in gate structures if steels with different electrochemical potential are used to construct or repair these structures. Generally, when a structure contains mixed steels, the more electrochemically active steel should be the one having the most surface area because it will be the steel exhibiting corrosion. This means that, to avoid galvanic corrosion, rivets and other fasteners with small surface area should be selected to be less electrochemically active than the structural steel plates or angles they connect. Galvanic corrosion is evidenced by blistering or discoloration of the paint and failure of the paint system adjacent to the contact area of the two steels. The corrosion at the rivets in Figure 20, identified above as crevice corrosion, could possibly also be galvanic corrosion. Galvanic corrosion decreases as the distance from the metal junction increases.

[1] M. R. Kaczinski, report of trip to St. Paul District Office, memo to project file, June 17, 1992. Attachment to letter, J. E. Bower to C. Chasten (WES), June 17, 1992.

**Stray-current corrosion.** Stray-current corrosion may occur if there are sources of externally induced electrical currents and if these currents follow paths other than what is intended. Electrical currents can arise from cathodic protection systems, electric deicing heaters, or even welding generators attached to the gate structures. If stray currents from these systems pass out of the gate through the water to ground, stray current corrosion could occur. Stray-current corrosion is essentially independent of environmental factors.

**Filiform corrosion.** Filiform corrosion occurs under thin paint films and initiates at a defect or crack in the paint film. It has the appearance of fine filaments emanating from the source in more or less random directions underneath the paint film. It was not observed during the onsite inspections; but, based on the failures of the paint system that were observed, it may occur.

## Mechanically assisted corrosion

Mechanically assisted corrosion is also possible in spillway gate structures. However, the possibility of serious deterioration on gate structures is less from mechanically assisted corrosion than from general atmospheric or localized corrosion.

**Erosion corrosion.** Erosion corrosion is caused by removal of surface material by action of numerous individual impacts of solid or liquid particles and usually has a direction associated with the metal removal. In the case of painted gates, the precursor of erosion corrosion would be directional removal of the paint film by the impacting particles. Erosion corrosion produces imprints of the impacting particles. This type of corrosion is possible in gate structures at steel or cast iron seal plates as was observed on the lift gates at Bankhead Lock and Dam.[1]

**Cavitation corrosion.** Cavitation corrosion is caused by formation and instantaneous collapse of tiny bubbles or voids when there is rapid and intense pressure changes such as caused by turbulent flow; the collapse can remove surface films such as oxides or paint and expose bare metal to corrosive conditions. Cavitation corrosion produces rounded microcraters.

**Fretting corrosion.** Fretting corrosion is a combination of wear and corrosion in which material is removed between contacting surfaces when very small amplitude motions occur between the surfaces. Red rust is formed and would be observed coming from between the contacting surfaces. Fretting corrosion might occur in gates if rivets become loose, fracture the paint system, and allow abrasive motion to occur between the loose rivets and the parts they fasten.

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1 M. R. Kaczinski, report of trip to Tuscaloosa office, memo to project file, May 19, 1992.

## Parameters Influencing Corrosion

The type and amount of corrosion which will occur at a specific location on the gates are dependent upon the details of the local electrochemical environment and the nature of the protective coatings present. Because the specific environment at one location of a gate can be different from a nearby location, and because the type and rate of corrosion is dependent upon the specific environment, corrosion can vary from location to location on the same gate. When comparing gates at different locations along a river, it is also possible to find that corrosion varies significantly because conditions are different.

### Electrochemical environment

A corrosion-inducing electrochemical potential will generally be established by one of four mechanisms:

*a.* A potential difference between two touching steel alloys.

*b.* Oxygen concentration differences where the low-oxygen region will be corroded (i.e., in a crevice or pit, or under a rivet or bolt).

*c.* Metal ion concentration differences where the low-metal-ion region will be corroded (i.e., outside of a crevice or pit, or adjacent to a rivet or bolt).

*d.* A variation of other ion concentrations (such as chloride) where the high ion concentration region will be corroded.

However, many external variables affect the local electrochemical environment; those most relevant to corrosion of spillway gates are summarized below:

a. *Temperature*. Higher temperatures increase the rate of corrosive attack.

*b.* *Relative humidity*. Corrosion of steel is significantly reduced when the relative humidity is less than 40 percent.

*c.* *Time of wetness*. The longer the time of wetness, the greater the corrosion. Importantly, though, corrosion is aggravated by alternately wet and dry cycles.

*d.* *pH of the river water*. Corrosion usually occurs at low pH (highly acidic conditions) and at high pH (highly alkaline conditions) while a protective oxide or hydroxide often occurs at intermediate pH.

*e.* *Ions in the river water*. Deicing salts accelerate corrosion.

*f. Film-forming materials.* Materials such as oil, grease, and tar in the river water can create crevices and ion concentration cells, and also can be involved in biological corrosion.

*g. Dirt, sand, gravel.* Debris in the river water can create crevices, ion concentration cells, and also can be involved in biological corrosion. Some of the heavy corrosion in Figure 19 was caused by an accumulation of debris in the filleted corner of the angle.

*h. Biological organisms in the river water.*

*i. pH of rain.*

*j. Ions in the rain such as $SO_x$ and $NO_x$ from acid rain.*

Basically, the external variables are the climate and the condition of the river water due to discharges from towns and industries, river traffic, and tributary rivers and streams.

## Protective coatings

Although paint and other protective coatings are preventative measures against corrosion, the effectiveness of protective coatings is dependent upon factors such as:

*a.* The pretreatment (type and degree of abrasive blasting or chemical cleaning) of the gate components prior to application of the primer coat.

*b.* Condition of the steel surface prior to application of the primer coat. The steel surface may rust and/or become contaminated between the time of pretreatment and the time of painting.

*c.* Type and thickness of the primer coating.

*d.* Type and thickness of the final coatings which protect the primer coating.

*e.* Geometrical factors such as sharp corners, crevices, rivets, and bolts which are difficult to adequately coat, with the consequence that they are less protected by the paint or coating system than the rest of the gate. Figure 21 depicts this effect on the edges of angles on a lift gate; Figure 22 shows it near a tack-welded edge on a tainter gate, and Figure 23 shows it on rivet heads.

If the gate has been completely repainted, all the preceding factors will determine the useful life of the paint system. However, if the gate is only partially repainted, the transition from the repainted areas to the unrepainted areas often will govern the useful life of the repainted system.

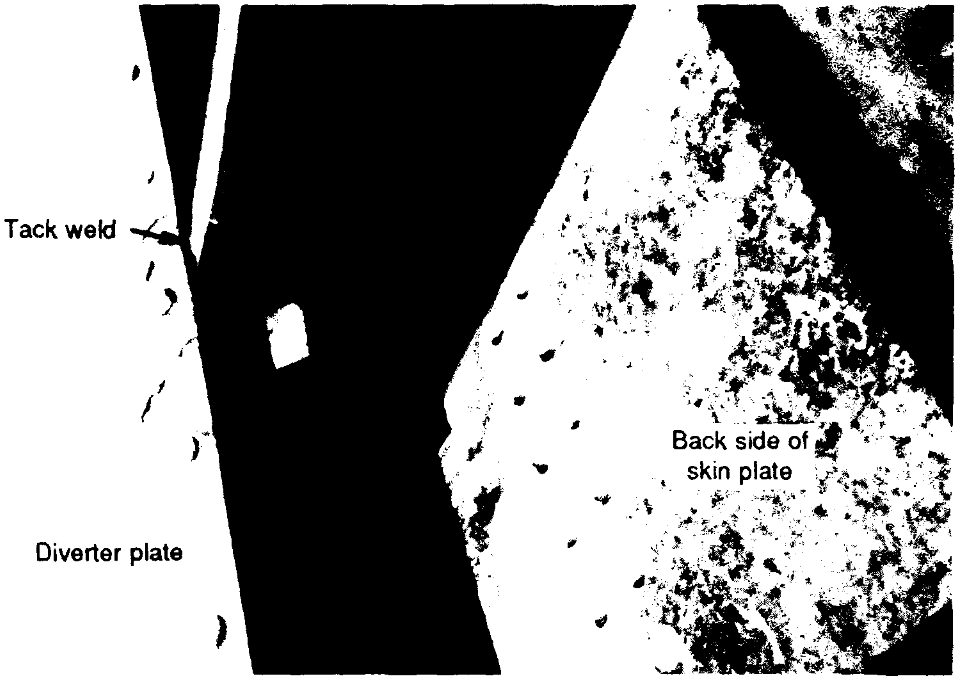



**Figure 22. Failure of paint system on tainter gate at edge of plate near tack weld, Mississippi Lock and Dam No. 9**

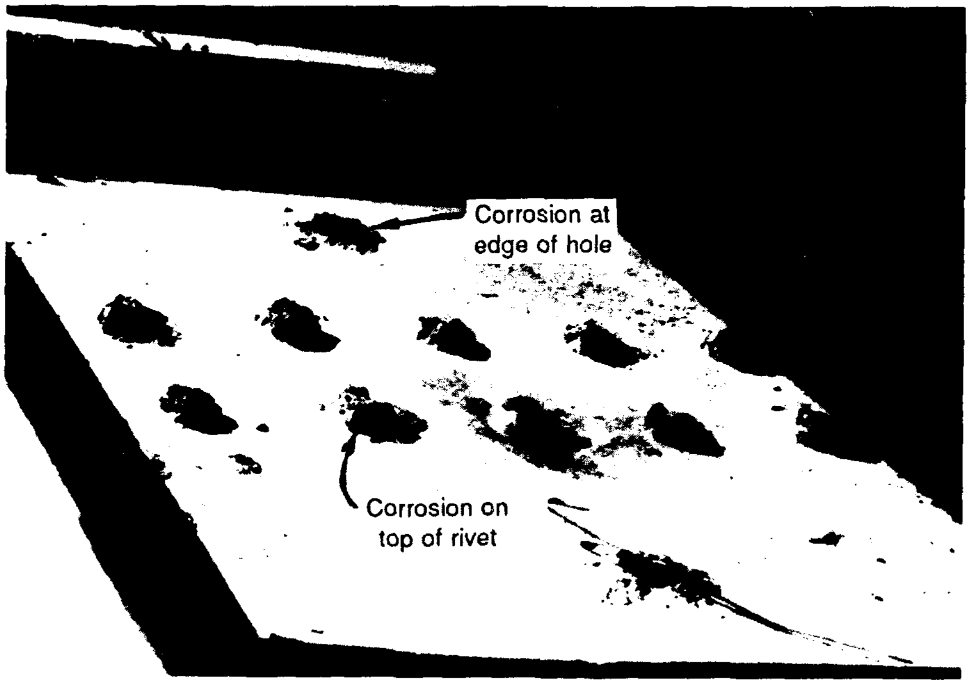



**Figure 23. Vertical lift gate at Bankhead Lock and Dam with corrosion of rivet heads**

Surface pretreatment including adequate cleaning is necessary for the transition zone and the area to be repainted.

It is extremely important that the pretreatment operations, primer, and final paint coating be uniform from location to location on the gate. Any variation in the paint system can cause local breakdown of the coating which can result in corrosion under the paint.

# 5 Task 4 - Effect of Repeated Loading on Gates

As described in Chapters 2 and 3, previous Corps experience and current observations during the site reviews indicated that Corps spillway gates (particularly tainter gates) are subject to occasional flow-induced vibrations, which cause cyclic stresses in the gates.

However, spillway gates have historically been designed assuming that all structural loads are applied statically (USACE 1966, 1962). Therefore, this chapter considers the possible causes of repeated or cyclic loads on riveted spillway gates and the locations and fatigue strength of riveted details on these gates. In addition, the fatigue-related effects of adding welds to the riveted gates are discussed.

## Origin of Repeated Loads

Since all spillway gates must be translated or rotated to release water, there are loads on these structural systems that are variable and repeated in nature. The most common sources of these loads are summarized below.

### Wind and wave action

This is a continuous phenomenon that to our knowledge has not caused any structural problems in spillway gates. In general, these loads can be regarded as low stress and low frequency, and are unlikely to cause fatigue damage.

### Gate lifting

During the routine operation of lifting spillway gates, cyclic loads are applied to structural members from two sources. The first source of cyclic loads is the change in hydrostatic pressure on a gate as it is pulled out

of the water and then resubmerged. Although this load case has the potential to produce large variation of stress in structural components, the frequency of occurrence (a worst case assumption is one cycle per day) may be too low to cause fatigue damage. The other potential source of cyclic loads is the damped vibration of impulse loads required to overcome the friction at side seals, particularly in heavy ice conditions and at trunnion pins.

The possibility of repeated loads due to gate lifting operations causing fatigue damage is unlikely. However, the potential for damage to structural components due to a single gate lift in extreme (loading) conditions is a serious consideration.

### Flow-induced vibration

This phenomenon produces the most significant cyclic loads on spillway gates because of the potential to combine live load stresses above the fatigue damage threshold with high frequencies. In fact, any gate which is discharging water may have some level of flow-induced vibration. Past experiences at spillway gates along the Arkansas (USACE 1971) and the Upper Mississippi Rivers (USACE 1986) have indicated that tainter gates are susceptible to severe vibration problems. From investigative studies at these sites, it has been found that the problem seems to be heavily influenced by flow conditions (i.e., gate opening and tailwater elevation) and bottom seal details. Vibrations were successfully reduced or eliminated by modifying the seal detail or simply operating the gate outside of the range which causes vibration.

## Fatigue of Riveted Structures

### Background

Fatigue of a metal structure is the phenomenon of crack development and failure of a member under repetitive loading. Fatigue strength of structural steel members is typically represented by $S_r$ - $N$ curves, where $S_r$ is the constant-amplitude stress range of the repeated stress cycle and $N$ is the number of stress cycles to the detection of a fatigue crack or to the failure of the cracked member. For welded structural members, several fatigue strength categories (A, B, B′, C, D, E, and E′) have been defined for fatigue design and evaluation of various types of weld details (Keating and Fisher 1989), as shown in Figure 24. These fatigue strength lines are based on the results of detecting visible cracks in test specimens, and have been verified by results from analytical studies. The dashed lines in Figure 24 represent the fatigue limits of the categories. If the $S_r$ at a weld detail is below the appropriate fatigue limit, no fatigue damage is assumed to occur.

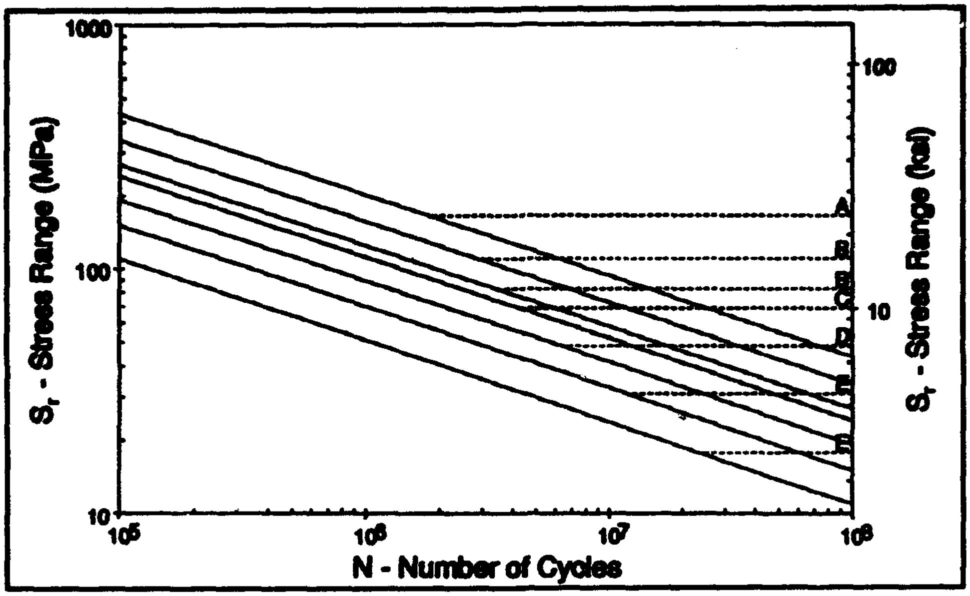



Figure 24. Current fatigue strength ($S_r$ - $N$) curves of AASHTO and AREA

For riveted structural members, however, no definite $S_r$ - $N$ curve has been established for fatigue design and evaluation. Current design provisions of the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 1989) and the American Railway Engineers Association (AREA) (AREA 1992) specify that the fatigue strength of riveted members be determined using the fatigue strength ($S_r$ - $N$) curves for Category C and Category D, even though the curves were developed for welded details. According to current AREA standards, the Category D curve should be used for riveted members when $S_r$ is 12 ksi or greater, and Category C should be used when $S_r$ is less than 12 ksi. It was concluded in Fisher et al. (1987) that the Category D curve provides an adequate reference for fatigue crack detection in riveted members, and the Category C curve is a reasonable estimate for fatigue strength before failure.

More test data are needed for the determination of a definite $S_r$ - $N$ curve or a set of curves for riveted members and connections, especially in the low-stress-range, high-cycle region. Research on this subject and on the fatigue crack growth rate in riveted members is currently being conducted by the ATLSS Center.

## Characteristics of riveted structural members

Both research findings and practical experiences have demonstrated that, when the magnitudes of live load stress ranges are not very high, riveted built-up members have a fatigue strength higher than suggested by the Category C or Category D curves for welded members. The contributing factors include the following:

*a*. The clamping force that develops as hot-driven rivets cool enhances the fatigue strength in the rivet hole area. The clamping force induces a friction bond between the riveted plates and, thus, decreases the crack growth rate.

b. The redundancy of multicomponent, built-up, riveted members prevents the sudden fracture of the structural member. Since cracks usually do not propagate from one component into adjacent components, fatigue cracking in riveted members is not continuous as in welded members. In other words, fatigue cracking in one component of a riveted structural member usually does not cause the failure of the member. Therefore, fatigue cracks would more likely be detected long before the riveted member's load carrying capacity is exhausted.

As is generally true in the phenomenon of fatigue, the most important factor governing the fatigue life of riveted structural members is the amplitude of the cyclic stress ranges applied to the riveted details. Conditions which influence the tightness of the rivets and the severity of local corrosion are also contributing factors. Furthermore, it has been observed in Fisher et al. (1987) that the fatigue strength of riveted members is relatively insensitive to the type of detail in the member. Test data showed that there is no significant difference observed in the fatigue strength of cover plate details, longitudinal splice plates and angles, or shear-splice details. It has also been found that rivet pattern is not a factor which affects the fatigue strength of riveted members.

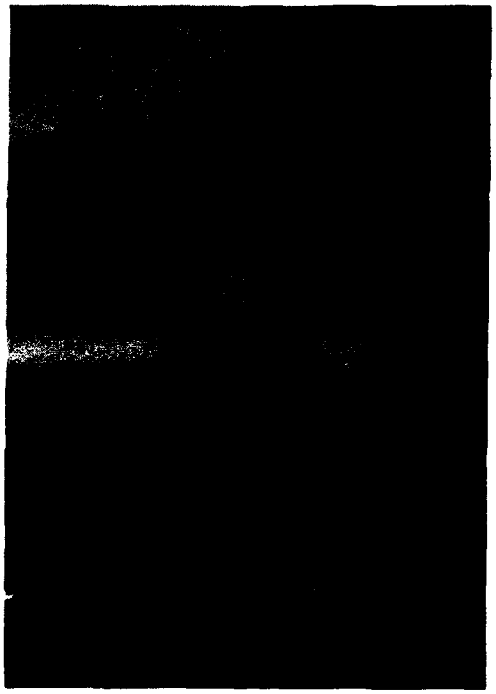


Figure 25. Typical fatigue cracking on riveted members

Cracking that propagates from a rivet hole is the typical phenomenon of fatigue damage of riveted members, as shown in Figure 25. Figure 26 is a close-up of the cracked surface showing that the crack initiated at the edge of a rivet hole. However, when corrosion is severe and the riveted member loses a large portion of its cross-sectional area, fatigue cracking may initiate from a corroded region. Figure 27 shows a fatigue crack initiated at a corrosion notch at the edge of a plate and propagated into a rivet hole instead of initiating at the hole.

### Fatigue test data from full-size riveted members

Many fatigue tests have been conducted on riveted structural members, using both small-scale specimens and the preferable full-size riveted bridge members. As a part of an ongoing research in this area, a literature survey has been

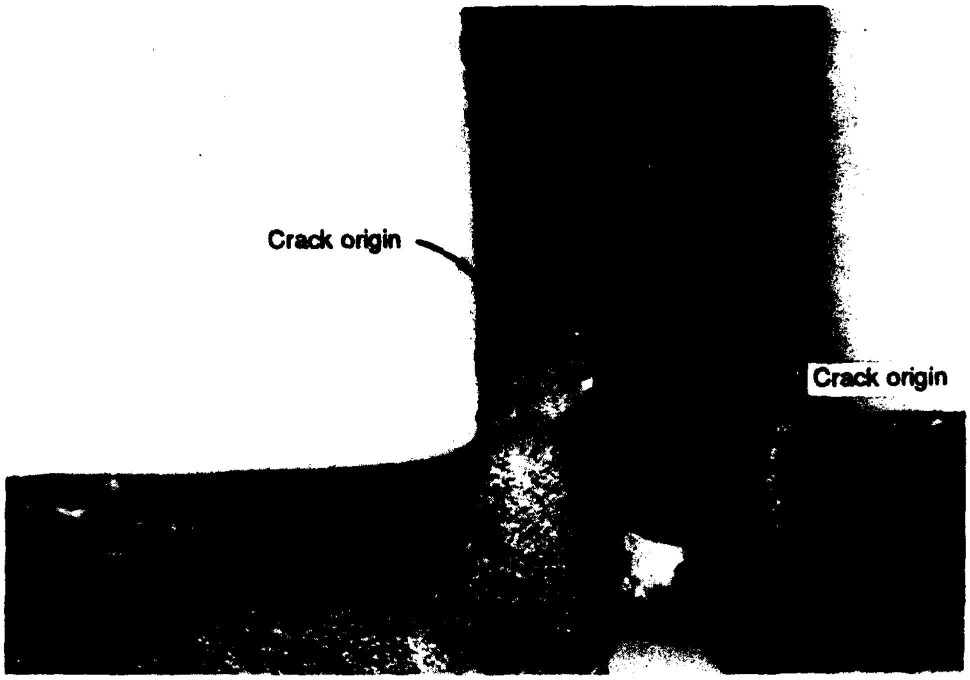


Figure 26. Crack surface at the edge of a rivet hole


Figure 27. Fatigue crack from corrosion notch into rivet hole

made of all the published data from fatigue testing full-size riveted members (Fisher et al. 1987). The database expands that of Fisher et al. (1987) and covers test results from as early as 1937 to date. The test members included full-size riveted connections under tension and full-size riveted built-up members under bending. The available data from these fatigue

tests are not abundant and are plotted in Figure 28 with the AASHTO fatigue strength ($S_r$ - $N$) curves of Categories C and D, which have been developed for welded details.

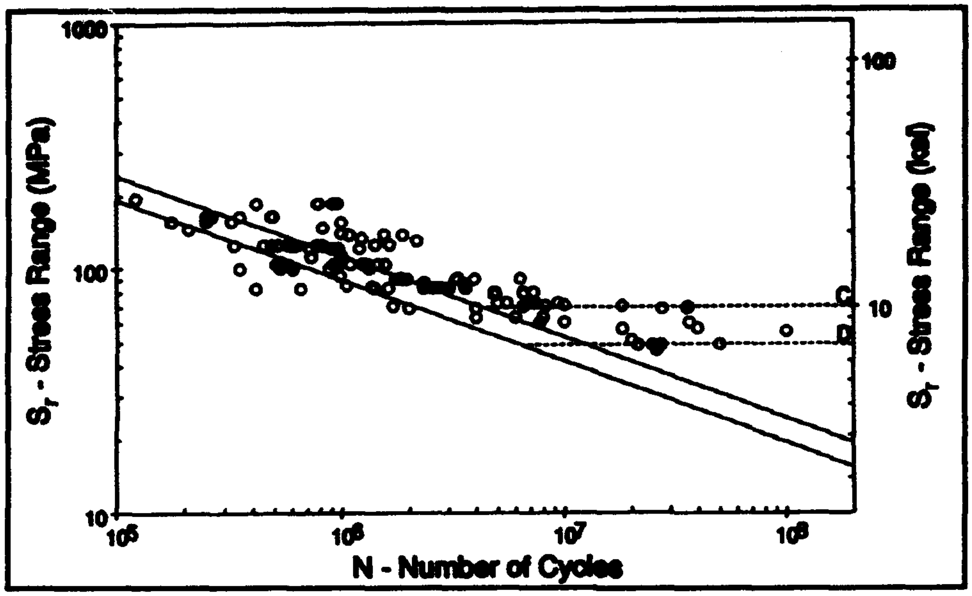



Figure 28. Available fatigue testing data from full-size riveted members

Although the available test data are not abundant and the conditions of failure at termination of testing are not defined, some conclusions can be drawn from these data. As seen in Figure 28, Category D provides a reasonable estimate of fatigue strength for structural details in full-size riveted members subjected to stress ranges higher than 10 ksi ($S_r \geq 10$ ksi), while Category C is a lower bound for the lower-stress-range, high-cycle region. There are insufficient data for a conclusion about the fatigue limit of riveted members; but no fatigue failure has ever occurred when the stress range ($S_r$) was below 6 ksi (Fisher et al. 1987), provided that the structure member or detail is not otherwise damaged or severely corroded.

## Variable-amplitude fatigue loading

Most of the fatigue test data and the $S_r$ - $N$ curves in Figure 24 were established from constant-amplitude cyclic loads. In reality, however, structural members are subjected to variable-amplitude cyclic loads resulting in a spectrum of stress ranges. Figure 29 gives an example of a stress range histogram compiled from measured live load stresses at a structural detail. In this figure, the abscissa is the stress range, $S_r$, and the ordinate represents the fractional frequency-of-occurrence, $\alpha$. For example, the $\alpha_i$ and $S_{ri}$ in Figure 29 show that 6.5 percent of the stress ranges are between 3.75 and 4.5 ksi.

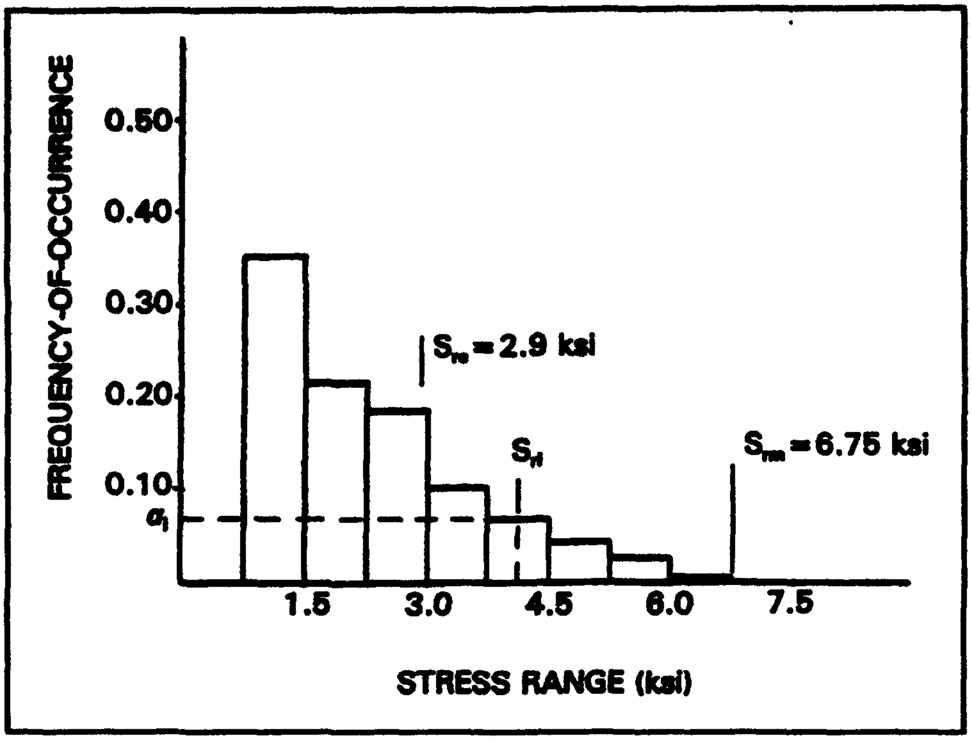



Figure 29. An example of a live load stress range histogram

To correlate the variable-amplitude stress ranges and the $S_r$ - $N$ curves, an equivalent constant-amplitude stress range, $S_{re}$, is calculated from the stress range histogram using the following formula:

$$S_{re} = \left(\sum \alpha_i \, S_{ri}^3\right)^{1/3} \tag{1}$$

A few of the data in Figure 28 were derived under variable-amplitude loads; their equivalent stress ranges have been plotted in Figure 28 against the corresponding stress cycles to the termination of testing. These data fit well with the constant-amplitude stress range data, which are the majority of the data.

## Recommended fatigue strength criteria for riveted spillway gates

To evaluate the fatigue strength of existing riveted spillway gates, it is recommended to use an approach similar to that of AREA, where the Category D curve is used for higher stress range, and the Category C curve is used for lower stress ranges. Based on the more recent test data, it is recommended to use the Category D curve for $S_r \geq 10$ ksi and the Category C curve for $S_r < 10$ ksi, with $S_r = 6$ ksi being the assumed fatigue limit. Figure 30 shows the composite $S_r$ - $N$ curve corresponding to this recommendation.

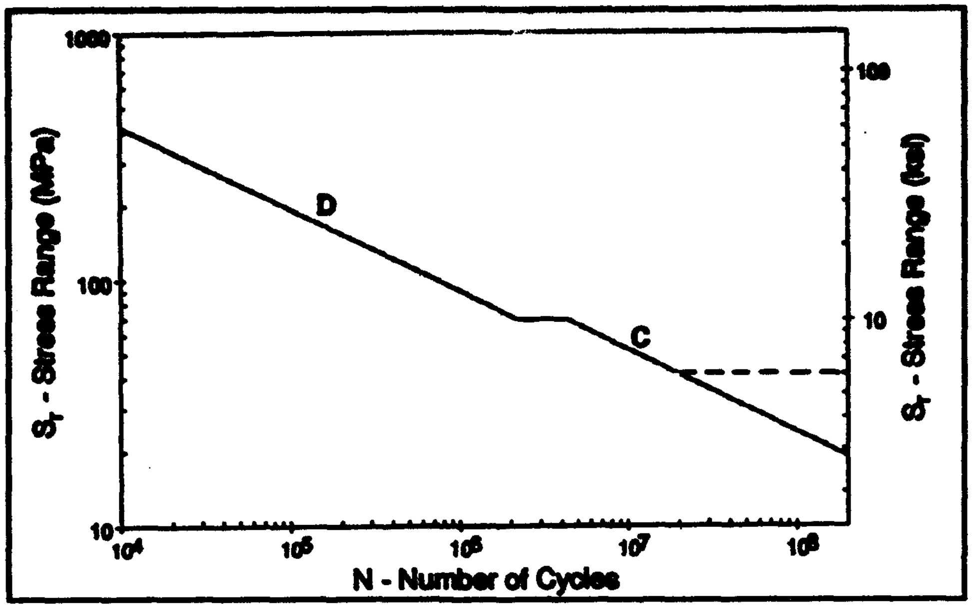



Figure 30. Recommended $S_r$ - $N$ curve for riveted spillway gates

The criteria described above are for riveted spillway gate members with only minor deterioration. For severely corroded members or members with corroded, loose or missing rivets where the clamping force is reduced or lost, lower fatigue strength curves may be more appropriate. Specifically, it is suggested that the Category E or E′ curves and the corresponding fatigue limits *should* be used, depending on the degree of corrosion. This is because, as shown earlier, fatigue cracks may initiate at corrosion notches instead of from rivet holes.

Figure 31 demonstrates the procedure of estimating the fatigue life, $N_e$, of a riveted spillway gate member which is subjected to variable-amplitude stress ranges represented by Figure 29. In this case, the highest stress range, $S_{rm}$, in the stress-range histogram is greater than 6 ksi, the assumed fatigue limit; eventual fatigue damage may occur. The estimated fatigue life is obtained by locating the intersection of the equivalent stress range, $S_{re}$, and the extension of the Category C line, as shown in Figure 31 (Keating and Fisher 1989; Fisher et al. 1987).

The recommended fatigue strength criteria for riveted spillway gates can be summarized as the following, for undamaged and noncorroded riveted spillway gate members and details:

When $S_{rm} \leq 6$ ksi, the possibility of fatigue damage can be ignored.

When $S_{re} < 10$ ksi, use Category C and $S_{re}$ to characterize the fatigue strength and life of the riveted member detail.

When $S_{re} \geq 10$ ksi, use Category D and $S_{re}$ to characterize the fatigue strength and life of the riveted member detail.

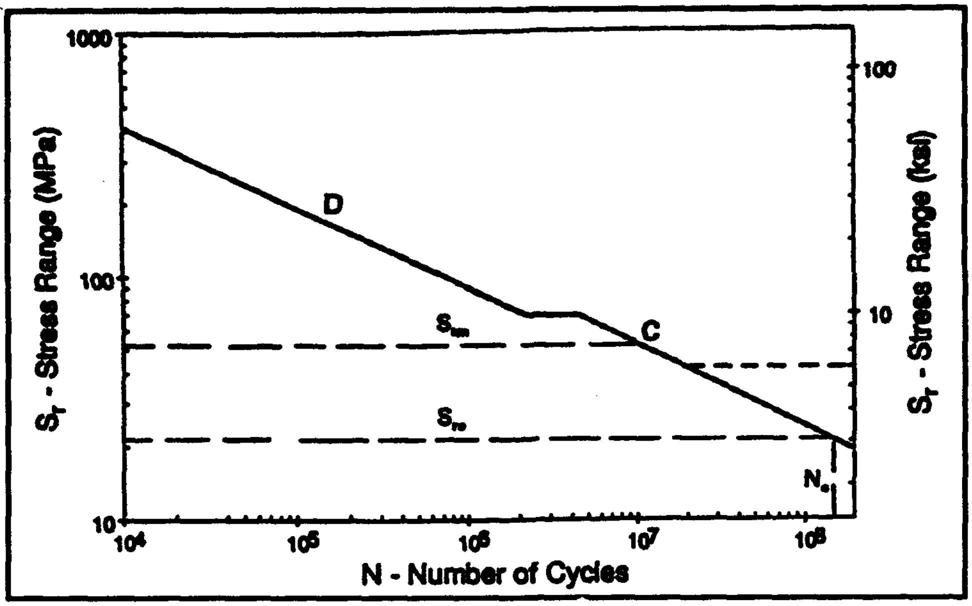



Figure 31. Estimation of fatigue life of riveted spillway gates members

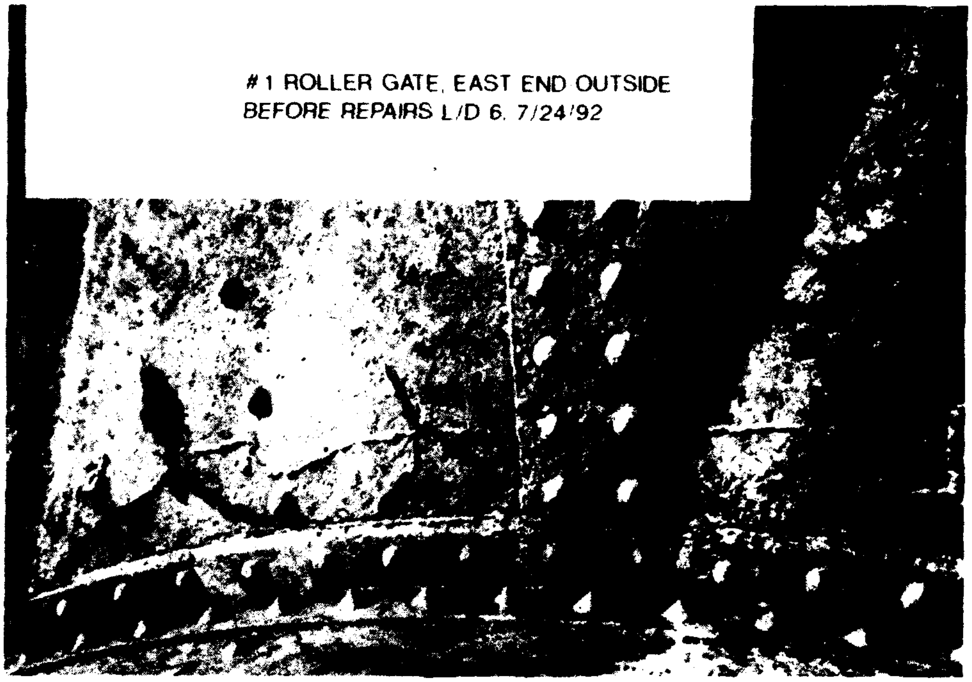
At the detail to be evaluated, $S_{rm}$ and $S_{re}$ are the highest stress ranges and the equivalent constant-amplitude stress range, respectively.

## Effect of Adding Weld Details to Riveted Structures

As mentioned earlier, attachments have been welded to riveted gates. Also, tack welds were observed to be common in riveted gates and may have been placed between components for the purpose of positioning and alignment before riveting. Because attachment welds and tack welds are usually unregulated and uninspected, relatively significant weld defects and residual stresses can occur. Moreover, as also mentioned earlier, the structural steels of the 1930's were not characterized as steels for welding. The seal welds that were used and observed at the spliced connections of adjacent skin plates to prevent water leakage, as shown in Figure 20, were probably better regulated. But, there too, significant weld defects could have occurred, particularly if the steel had poor weldability.

Adding welds to riveted structures can reduce the fatigue strength of the riveted member and lead to the development of fatigue cracks if the live load stress ranges are high enough. Attachments, tack welds, and even seal welds may lower the fatigue strength of a detail to Category E or E′. Figure 32a shows fatigue cracks initiating from the ends of welded stiffeners in the end shield of a riveted roller gate at Mississippi River

a. Fatigue cracks at ends of welded stiffeners on roller gate end shield




b. Fatigue cracks redeveloped at previous repair welds

Figure 32. Fatigue cracks

Dam No. 6 in the St. Paul District.[1] Figure 32b indicates cracks reinitiating from previous repair welds. In this instance, attempts to strengthen a riveted gate by adding welded stiffening plates created very poor fatigue details. Repairs such as this should be avoided. Figure 33 shows a fatigue crack starting from a tack weld on a riveted bridge member. The crack initiated at the toe of the tack weld and grew into the riveted plate in the direction perpendicular to the primary tensile stress. Similar damage could occur on a riveted gate member.

Figure 33. Fatigue crack initiating from a tack weld on a riveted member

1 Letter, K. D. Hokens (St. Paul District) to C. Chasten (WES), August 6, 1992.

# 6 Task 5 - Structural Evaluation Guidelines

This task, developing guidelines for conducting a structural evaluation of riveted spillway gates, was the primary task of the entire study. The method used was to divide the evaluation procedure into its critical components and then address these components sequentially. The findings from earlier tasks provided the background material for conducting this process. Then, using the evaluation process, examples are presented to demonstrate the application of the proposed guidelines. Finally, recommendations for continuing evaluations are made.

## Components of a Structural Evaluation

Guidelines for conducting a structural evaluation of riveted spillway gates must identify and define the steps leading to the judgment of the gate's structural integrity. Therefore, in this chapter, four steps are identified and defined both generally and in terms of the questions that each step addresses and the potential responses to these questions. The four steps of a structural evaluation are:

*a*. Preinspection assessment.

*b*. Inspection.

*c*. Assessment.

*d*. Recommendations.

## Preinspection assessment

Preinspection assessment consists of reviewing design drawings, previous evaluation reports, and all operations/maintenance records since the most recent inspection. In addition, all critical areas or components of the gate structure should be identified.

Before travelling to the site and conducting an inspection of the spillway gates, the inspector should prepare by reviewing all available documentation. In the review of existing documents, the following question should be asked: "Are there suspected preinspection conditions, or have critical circumstances occurred since the most recent inspection?" These conditions include the following:

*a.* A history of problems.

*b.* Newly reported extreme loads.

*c.* A change in operational practice.

*d.* Unusual events.

Specifically, to answer this question, the inspector should do the following:

*a.* Review the structural drawing of the gates to become familiar with the gate components and operation. Locations and details on the riveted gate structure subjected to high stresses or prone to fatigue damage and susceptible to corrosion should be identified. These locations should receive more attention during the inspection.

*b.* Review previous inspection reports, if any, to find out whether any structural damage or potential problems were noted on the last inspection. If problems were detected, make note of the location and determine if any repairs were performed. In the case of fatigue cracks repaired by welding, the cracks often reinitiate at the same locations if no changes to the structural configuration have been made.

*c.* Search for notes of special events, such as records of gate vibration, frequent malfunctioning of the operating mechanism (e.g., uneven hoist cable movement), repeated difficulties in initiating the opening or closing of the gate (causing impulse loads to the gate when static friction was overcome), impact loads on the gate structure from floating debris, and unusually high seasonal loads (e.g., ice). These events could have imposed high magnitude stresses and/or a large number of stress cycles which may cause fatigue cracks to develop or members to buckle.

A proposed checklist follows:

**Structural elements.** For simplicity, the identification of critical structural locations on riveted tainter and vertical lift spillway gates can be subdivided into the following areas: lifting assembly, main framing members, and skin plate. Because of the unique method of operation of roller gates, the identification of critical locations is better subdivided into only two areas, main framing members and skin plate. A more comprehensive discussion of all components of gate structures was presented in Chapter 2.

a. *Tainter gates.* The critical components in the lifting assembly on a tainter gate consist of the hoist mechanism, trunnion assembly, and seals. A nonredundant chain or wire rope located at each end of the structure is usually used to lift spillway gates. Because these member are nonredundant, they should be kept in good condition with little corrosion. The trunnion assembly should be kept well lubricated to prevent excessive friction forces from being developed when the gate is being lifted. Side seal rubbing plates should be kept clean and smooth to prevent corrosion and should be free of ice before attempting to lift a gate in extreme weather conditions.

   Main structural framing members which should always be carefully inspected include the vertical ribs, horizontal girders, and end frames. Because of the application of concentrated loads at the hoist bearing plate, ribs in this vicinity should be carefully examined for local buckling. Both the horizontal girders and the end frames should be inspected for global and local buckling (particularly near the knee brace intersection) and should have properly located and unclogged drain holes to prevent corrosion.

   The skin plate should be inspected for corrosion loss, missing or deteriorated rivets, and damage due to impact from debris. Although it is difficult to visually inspect the entire surface of the skin plate, most problems would be expected to occur in the upper section of the gate in the splash zone.

b. *Lift gates.* The critical components in the lifting assembly on a vertical lift gate consist of the lifting hooks, end bearings, tracks, and guides. Because of their nonredundant application and the concentration of loads at this location, the lifting cable and hooks should be well maintained. The end bearing assembly should be properly lubricated and inspected to ensure that the wheel alignment and track surface finish are at tolerances which prevent local overloads. To minimize lifting loads, tracks should be flat, and both tracks and guides should be free of debris and corrosion.

   The main structural framing members in a lift gate consist of the horizontal girders and end posts. Because of their horizontal orientation, the webs of the girders should be inspected for corrosion and the drain holes should be kept clear of debris. The top girder should

be carefully inspected near the lifting hook attachment for local member buckling.

Similar to the skin plate on tainter gates, the skin plate assembly on lift gates (skin plate, vertical beams, and intercostals) should be inspected for corrosion loss, missing or deteriorated rivets, and damage due to impact from debris.

c. *Roller gates.* The primary structural framing members of a roller gate consist of a drum assembly, apron assembly, and end disks. Without lifting the gate out of the water and providing access to the inside of the drum assembly, a thorough inspection of the structural members and connections between the members is very difficult. However, while in the closed position, the top portion of the skin plate can be inspected for corrosion and damage due to impact from debris.

**Corrosion susceptible areas.** Several types of corrosion can occur on spillway gates. These types, fully described in Chapter 4, have identifiable characteristics and occur in particularly susceptible areas. A review of these should be part of the preinspection step.

Generally, any failure of the paint system on a gate should alert an inspector to underlying corrosion. If there is a widespread failure of the paint system, general corrosion with a slow, relatively uniform thinning of the base metal may be occurring. Moreover, some localized pitting corrosion may be present.

If there is a localized failure of the paint system, localized corrosion may be occurring. Paint failure where the edges of two or more surfaces contact, such as at the edge of a rivet head or at the edge of an angle riveted to a plate, may indicate crevice corrosion, or galvanic corrosion if the surfaces are dissimilar metals, or even fretting corrosion if there is a loose rivet or if other contacting surfaces are loose. If paint failure is occurring near electrical connections on the gate, it may be stray current corrosion. If the paint failure is patterned, or preferential in appearance, it may be due to filiform corrosion under the paint or to mechanically assisted corrosion—either fretting or erosion corrosion. At seals, where heavy corrosion has occurred in the past, there may be galvanic corrosion if the seal plate is a dissimilar metal to the gate itself; or there may be erosion corrosion if abrasive sand and silt particles are passing through.

The structural members on many gates have their webs oriented horizontally or radially. To prevent ponding of water on these webs, the webs of these members are penetrated by drain holes. The hole locations can be corrosion-susceptible areas, however, if they are covered with debris. Therefore, the location of web drain holes should be determined during the preinspection.

Other corrosion-susceptible areas are those involving moving parts; for example, the guide wheels on vertical lift gates and the trunnion assemblies on tainter gates involve moving parts. The hoist areas are susceptible too, because they provide crevice sites and may include dissimilar materials.

**Fatigue sensitive details.** A checklist of locations (both specific and general) which are susceptible to fatigue cracking and fracture is presented below to assist the inspector during the preinspection. While reviewing plans of the spillway gate, the inspector should document any fatigue-critical areas located on the structure. Locations include:

*a.* Previous cracks repaired by welding, either by deposit of weld beads over the cracks or by covering the cracks with doubler plates. Figure 34 shows an example of cracks redeveloped at weld repairs.

*b.* Locations where the structural configuration is similar to where cracks from rivet holes have been detected.

*c.* Riveted connections between components such as that between a roller drum cylinder and the end shields (Figure 35) where the rigidity of the connection prevents the movement of one component against the other. When a gate is being opened or closed, or when high-velocity water flows by the gate, relative local displacement may occur between two rigidly connected components and induce high stress ranges (live load stress). If the occurrence of these stresses is frequent (high number of cycles), fatigue cracks may develop.

*d.* Flange-to-web junction of horizontal girders opposite skin plate ribs, where concentrated loads are transmitted between the ribs and the girder. Localized concentrated loads sometimes induce high local stresses and movement of the connection angles, resulting in fatigue cracks from rivet holes in the connection angles.

*e.* Seal welds in skin plates, particularly when the seal weld is subjected to repeated loads during operation of the gate.

*f.* Components subjected to high frequency, flow-induced vibration. The lower sill of tainter gates, the apron assembly of roller gates, and the end shield of roller gates are examples.

*g.* Tack welds at high tensile stress areas of components, especially at locations cited above. The downstream flange-to-web junction of horizontal girders in tainter gates and the junction between a skin plate and its vertical ribs or beams frequently have tack welds (Figure 22). These tack welds which are not able to resist the relative movement between components may develop cracks which can ow into the gate components. Similarly, any field-welded

Figure 34. Fatigue cracks redeveloping at weld repair sites on roller gate end shield


Figure 35. Fatigue crack at connection of roller gate cylinder and end shield

**attachments such as stiffeners or repairs which were added to riveted members are fatigue-sensitive areas.**

*h.* **All stress concentration areas such as the hoist cable connection to skin plates.**

*i.* **Areas where corrosion has reduced the cross-sectional area and created notches in members.**

## Inspection

The activity of examining, measuring, testing, gauging, and using other procedures to ascertain quality, detect defects or deterioration, or otherwise appraise a gate and its materials, components, and systems should be done while the gate is in use and, to the extent possible, raised out of water. To effectively conduct an inspection, the gate structure should be systematically examined from one end to the other and from the top to the bottom. Particular attention should be given to the critical locations cited in the preinspection assessment. All observations should be documented in sufficient detail.

While inspecting the various components of a spillway gate, the following questions should be asked:

*a.* Is there a condition to report for the main structural elements?

(1) Overall or local buckling or deformation.

(2) Loose rivets.

(3) Fabrication defects.

*b.* Is there a condition to report for the mechanical/electrical components?

(1) Seal problems.

(2) Hoist guides, bearings, heaters.

*c.* Is corrosion evident?

(1) Paint loss.

(2) Cross section loss.

(3) Discoloration.

*d.* Are any fatigue cracks visible?

(1) Near rivets.

(2) At corroded areas.

(3) At any welds.

*e*. Have unusual conditions been observed?

(1) Vibration.

(2) Severe seasonal loadings.

Some special considerations concerning these questions follow.

**Inspecting for corrosion.** Three common nondestructive evaluation (NDE) techniques can be applied for inspecting spillway gate structures for damage due to corrosion: visual inspection, ultrasonic inspection, and radiographic inspection.

Prior to inspection, tools to assist in measuring and defining the corrosion mechanism should be gathered. These would include a depth micrometer (for pitting), feeler gauges (for crevice corrosion), an ultrasonic thickness gauge (for thinning), a hammer—ball peen or instrumented—(for loose rivets), a camera, a tape measure, and a means to collect water samples.

Visual inspection is the primary NDE technique for locating, identifying, and determining the extent of corrosion. It has the benefits of being able to be done insitu at the gate and usually with only ordinary lighting. A visual inspection should be made of all corrosion-susceptible sites. These include:

*a*. Any area where the paint system has failed.

*b*. Around rivet heads.

*c*. At crevice sites.

*d*. Near drain holes in girder webs and at areas of standing water.

*e*. At moving parts such as guide wheels and trunnion pins.

*f*. At hoists.

*g*. At seals.

*h*. At electrical connections.

The extent of paint system failure should be recorded, particularly for the corrosion-susceptible areas. Regions of localized discoloration of gate components should also be recorded. In areas where paint failure has occurred, the gate surface also should be visually examined for pitting. When pitting is present, it should be quantified by using a probe-type depth gauge and following the standard ASTM practice (ASTM 1976).

Crevice sites for corrosion abound in riveted gate structures because of member discontinuities and edges inherent in riveted design. Moreover, this is aggravated because edges are very susceptible to paint failure. Thus, the extent of corrosion in these areas needs to be recorded during each inspection. A sheet-type feeler gauge may be used to quantify the width of a crevice exhibiting corrosion. Measuring the depth of the crevice (distance into the crevice) may be difficult due to corrosion product already being at the base of the crevice and blocking the gauge.

When corrosion is evident around rivet heads, deterioration of the rivet head and rivet should be looked for. The amount of head deterioration should be recorded and compared with the guidelines recommended later for rivet replacement.

Seals and hoist mechanisms represent gate areas with no redundancy but provide essential gate functions. Thus, to prevent developing a condition that limits gate operation, there is a strong need to visually inspect these areas and to record the extent of corrosion.

When extensive paint system failure is evident, samples of the river water should be collected for analysis for corrosiveness (see Chapter 5).

Ultrasonic inspection is useful when corrosion appears to have advanced to the degree that the structural gate components may be losing significant thickness or to obtain a baseline reference for thickness when it is unknown.

The thickness of a steel plate or part can be determined by ultrasonic techniques to an accuracy of ±0.005 in. The technique can be done through a paint film and through surface corrosion with only a slight loss in accuracy. Moreover, ultrasonic transducers are available in a number of sizes. Thus, ultrasonic inspection is useful in determining both general and localized thickness loss due to corrosion, even on the curved skin plates of gates. Moreover, it can be used when only one side of the gate is accessible. However, ultrasonic inspection to determine thickness is generally not reliable when pitting corrosion is prevalent because the size and depth of the pitting impair the output of the transducer.

When ultrasonic inspection is used, the transducer must be coupled to the steel using a coupling liquid, but this is not a serious limitation. It is usual practice to manually scan the surface with the transducer and develop a map of thickness variation to determine where corrosion has occurred. Methods and equipment for automated scanning and mapping of

thickness variation are available but are probably not economically justifiable for insitu use on gates.

Radiography, or X-raying, is an NDE technique which can be used to determine thickness loss due to corrosion, but it only has an accuracy of 2 percent of the wall thickness and thus is useful only for loss greater than this. Moreover, the technique requires access to both sides of the part being radiographed, which adds to the time and cost of the technique.

Newer methods of inspecting for corrosion are developing, such as magnetic resonance testing, but these are not yet ready for routine implementation.

**Inspecting for fatigue cracks.** A recommended procedure for inspecting riveted spillway gates for fatigue cracks is presented below. This procedure can be followed at all fatigue-sensitive areas on the structure identified during the preinspection assessment.

*a.* Examine the gate. Visual examination, particularly with the aid of a magnifying glass (5× or higher), is the most efficient first step.

*b.* Confirm presence of crack(s). If cracks are suspected and the gate component is dry, liquid penetrant can be used to confirm the presence of a crack. More sophisticated methods, such as the use of ultrasonic and magnetic instruments, can also be employed but may not be needed.

*c.* Record the location, orientation, and length of the cracks. Record conditions of the gate when cracks are detected.

*d.* Take photographs of all cracks showing their position relative to the components of the gate structure.

*e.* Compare the conditions of the detected cracks with previously located cracks, if any, before last repair.

**Inspecting for deteriorating rivets.** As observed during the onsite inspections, deterioration of rivet heads due to corrosion does occur. This deterioration can be critical and must be looked for during inspection. The consequences of rivet-head deterioration are: the rivet can no longer sustain the applied tensile force due to smaller head area; the rivet becomes loose and can no longer hold the connection tight; joint behavior such as prying may be exacerbated due to reduced head projection beyond the shank of the rivet; and the rivet will need to be replaced because it is missing or one of its heads has excessively deteriorated.

Figure 23 shows where rivet heads have split; that is, the rivets have developed rosette heads. These are readily observable in an inspection of a gate. Headless rivets are also easy to observe, if deterioration has

progressed that far. Generally, the degree of head loss (the degree of reduced projection from the shank) should be noted. Is the projection 20 percent, 50 percent, or 70 percent of the original head projection?

In some cases, a corrosion pattern around the rivet will suggest looseness or further corrosion occurring somewhere beneath the rivet head. Figure 20 shows such a corrosion pattern. The pattern may result from crevice corrosion where corrosion has penetrated the crevice between the rivet head and the connected parts; it may also result from a crack that has formed at the edge of the rivet hole; or it may result from looseness and motion between the rivet head and the connected parts. The corrosion pattern should always be recorded in these instances.

Inspecting for loose rivets may not be possible using only visual means. Supplemental inspection tests should be done if loose rivets are suspected. A commonly practiced nonvisual inspection technique is to transversely impact the rivet head with a hammer and judge the "give" or "ring" of the head. A newer technique is to impact the rivet longitudinally with a commercially available, instrumented impact hammer. These hammers, which generally include a built-in load cell, provide a vibration signal from the load cell. By capturing this signal with a monitoring unit, the signal can be compared with the vibration signal emanating from a rivet known to be tight or to the vibration signal resulting from tapping a separate, tightly clamped connection. The magnitude of the impact force must be consistent through these comparisons. Generally, the signal from a loose rivet will have a lower and broader frequency content than the signal from a sound rivet.

## Assessment

Assessment is the systematic collection and analysis of (a) inspection data, (b) documents including drawings and previous assessments and evaluations, and (c) loading and performance criteria regarding an existing gate, which relate to the continuing normal use of the gate.

What will happen if the condition continues?

*a*. The condition is minor, and of no consequence to normal use.

*b*. There is some deterioration or problem, but operation and structural capacity are not jeopardized at this time.

c. There is advanced deterioration or a serious problem and either the operation or the structural capacity could be affected.

Guidelines are presented below on assessing six conditions commonly encountered in the evaluation of riveted spillway gates: buckled or plastically deformed structural members, damaged lifting mechanisms, corrosion, fatigue cracking, rivet replacement and weld repairs.

**Buckled or plastically deformed structural members.** When buckled or plastically deformed structural members are found during the inspection of a spillway gate, an assessment must be made of the strength and serviceability of these members. To accurately assess the effect of the reported condition, detailed information must be obtained from the inspection report. This information should include:

*a*. Location of damaged (deformed) member.

*b*. Components of member damaged (i.e., web or flange).

*c*. Detailed description of damage including magnitude and wavelength of buckle.

*d*. Condition of adjacent members.

*e*. Possible cause of damage.

*f*. Effect of deformation on gate performance (if any).

If it is determined that the deformation was caused by an unusual or extreme event, and is limited to a small area on one member and does not affect gate performance, immediate repairs would most likely not be necessary. In this case, the damaged area should be closely monitored through more frequent inspections to see if the condition deteriorates. If these more frequent inspections reveal that the amount of damage is increasing or is spreading to adjacent members as the load is redistributed, a simplified analysis of the structure should be conducted. It would be satisfactory to use a two-dimensional (preferable) or three-dimensional model which places hinges in the member at the location of damage. In more severe cases, it would be preferred to assume the member is removed. However, in a situation where the amount of damage is continuously increasing, a repair or replacement of the member(s) should be scheduled immediately.

**Damaged lifting mechanisms.** If distress or damage is reported for the lifting mechanism of a gate, the problem should first be classified as either mechanical or structural in nature. If the condition reflects a structural problem, details on which member of the lifting mechanism (lift hoist or connection to gate) is damaged and the type of damage (e.g., frayed or misaligned cable, or cracked connection fitting) are necessary to make an accurate assessment. It should also be noted whether the condition may have been caused by previous structural damage to the gate, or whether it has caused damage to other components of the gate. In general, because the lifting assembly is a nonredundant structural element, any problems should be corrected immediately by either maintenance, repair, or replacement.

**Corroded members.** When corrosion is reported, the assessor should: (a) identify the type of corrosion and its possible cause, (b) for severe corrosion, identify specific members and locations, and (c) assess the effect of the corrosion on the section properties and functional performance of the members.

Corrosion typically is a slow-growth process. Therefore, if rapidly developing corrosion is reported, air and water samples should be collected and analyzed to check for unusual changes. If crevice corrosion is becoming more severe, consideration should be given to maintenance of the region during a regular maintenance period, including eliminating any buildup of corrosion product and then recoating with a more effective crevice-sealing coating or paint.

When specific members are affected by corrosion, the portion of the member most affected should be assessed. For example, if the member is a flexural member, does the corrosion have an effect on either the bending moment capacity or the shear capacity of the member? Measuring the remaining section thicknesses may be necessary to make this determination. If the section properties are reduced more than about 10 percent, a new analysis of the structure should probably be made. If the reduction is greater than 25 percent, consideration should be given to replacing the member during the next scheduled maintenance if the member is functionally critical.

**Members with fatigue cracks.** When a fatigue crack is detected in a gate structural component, the important items for consideration in assessment are the following:

*a.* Which member and detail exhibit the crack?

*b.* Is the crack growing?

*c.* Is the crack significant if it continues to grow?

*d.* Is remedial action needed urgently?

Cracks in nonredundant members or components are significant and require more attention. Hoist cables and attachment points of lifting mechanisms to the gate, for example, are nonredundant; continued crack growth could cause fracture of these components and impair the operation of the gate. Cracks such as those in the roller gate end shield shown in Figure 32 do not pose danger of imminent failure of the gate.

To determine whether a crack is growing and what the growth rate is, requires nondestructive monitoring. However, unless the crack is caused by flow-induced vibration and is in a nonredundant component of the gate, nondestructive evaluation usually is not necessary.

The majority of known cracks in gates have been found in redundant components; repairing these cracks does not need to be made urgently. It is more important to assess the cause of the crack and then to repair accordingly.

**Rivet replacement.** When there are deteriorating rivet heads, one reasonable recommendation has been (Fazio and Fazio 1984) to replace any rivet where 50 percent or more of head projection beyond the shank is missing if the rivet is subject to an applied tensile force or tension resulting from prying action. Corollary recommendations are to replace missing rivets, loose rivets, headless rivets, and rivets with rosette heads.

It is also important to adhere to the following guidelines for what not to do for deteriorating rivet heads. These guidelines are: rivet heads with rosettes and rivet heads with deteriorating projections should not be built up using weld metal or other materials (brazing, caulking) since these could aggravate rather than remediate the condition.

The current (1990's) practice for replacing rivets on structures such as gates involves using high-strength bolts as the replacement fasteners. These bolts have greater strength than the rivets they replace. However, removing the deteriorated rivet is sometimes difficult. The most accepted current method of rivet removal (Birk 1989) is to knock off the rivet head using a pneumatic "rivet buster" and then force the rivet shaft out of its hole using a powered impact tool. If needed, the rivet hole is drilled out to obtain an aligned hole through the connected parts. Then the high-strength bolt is installed and tightened by an accepted method such as the turn-of-the-nut method.

Unfortunately, one generally unacceptable method of rivet removal is often used. This method involves an acetylene torch which is used to remove the rivet head and shaft (Birk 1989). This technique can cause metallurgical damage to the gate structure due to heat and also has a higher risk of causing local damage such as burn gouges which can then adversely affect fatigue strength and corrosivity. Burning off rivet heads should only be done when there are experienced burners and a supervised environment, and pneumatic rivet busters are unavailable.

**Weld repairs.** If welds for repairs or to add components on riveted structures must be made, the riveted gate must first be judged (through trials or tests) to have adequate weldability. Then, the welds must be made according to Table 1 and today's structural welding codes.

The welded details need to be assessed for fatigue strength using the appropriate fatigue criteria and methods in Chapter 5.

## Recommendations

The final step in a structural evaluation is the recommendations. The recommendation is the process of determining the structural adequacy of a gate for its intended use and making fragment judgments about remediation of problems and frequency of inspections. Personal and subjective judgment by the persons functioning as expert evaluators is implied. The question to be asked is: What needs to be done to remedy the condition? Possible answers include:

*a.* Continue normal gate operation with only a periodic watch on a specified condition.

*b.* Continue normal gate operation with a programmed outage for either repairs, another inspection, or performance measurements.

*c.* Alleviate the loading by changing gate operational practice, before continuing gate use.

*d.* Discontinue gate use and make urgent repairs and/or measurements.

The current Corps inspection and evaluation program specifies that spillway gates must be inspected every 5 years (USACE 1988). This inspection interval is adequate if a thorough evaluation of the gate structure reveals no evidence of distress or potential failure. However, if significant deficient conditions exist (e.g., heavy corrosion, fatigue cracks, or deformations) or severe operations occur (e.g., persistent vibrations), it is recommended that a shorter inspection interval be used to ensure the structural and operational integrity of the gate structure. Because the conditions at each site are unique, proposing a general guideline for selecting shorter inspection intervals would be difficult and should be evaluated on a case-by-case basis. An example of selecting a reduced inspection interval is presented in the application examples which follow.

Maintenance operations should be continuous since a comprehensive program can reduce the occurrence of significant structural distress. In particular, through a regularly scheduled cleaning and painting program, the effects of corrosion can be controlled; and by removing debris and lubricating all mechanical components, the potential overloads from lifting operations can be minimized.

## Application Examples

### Example 1

An example is presented below to demonstrate the proposed guidelines for conducting a structural evaluation of riveted spillway gates. This case study is based on the results of the May 28, 1992, inspection of the riveted tainter gates at Lock and Dam No. 5 on the Upper Mississippi River near Winona, MN.[1]

Following the example application, which is based on inspection results, an additional example is presented which is based on hypothetical inspection results. This additional example assumes that significant cyclic stresses have been measured in the gate, and an assessment must be made of the structural integrity.

**Preinspection assessment.** The tainter gates at Lock and Dam No. 5 are 35 ft wide, 15 ft high, and 25 ft in radius from the trunnion pin to the face of the skin plate. The structure is framed similar to the design and detail provisions for tainter gates in EM 1110-2-2702 (USACE 1966) with a 3/8-in. skin plate, C12 × 25 vertical ribs, two W30 × 118 horizontal girders, and W18 × 80 strut arm frames. All connections are riveted except for the use of bolts at the strut arm-trunnion block detail. The non-submersible gates use Type J side and bottom seal details, which have been vibration-prone in the past.

The gates at Lock and Dam No. 5 have a history of structural problems which include significant gate vibrations (USAED, St. Paul 1988) and buckled web and flange plates on the strut arm.[2] No extreme loads or unusual events were reported in the time interval since the last inspection. A change in operational practice was instituted to avoid gate opening settings which cause structural vibration. Because of the history of problems at this site, a thorough visual inspection was made previously on several gates.

**Inspection.** On May 28, 1992, visual inspection was made of all 28 riveted tainter gates at Dam No. 5, and a more in-depth inspection was made of gates 23 and 24. Weather conditions at the damsite during the inspection were sunny and warm with temperatures in the 70's. The in-depth examination was conducted while water was being released from the gates and followed the inspection checklist provided earlier in this chapter.

The results of the examination are listed below:

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1 M. R. Kaczinski, report of trip to St. Paul District office, memo to project file, June 17, 1992. Attached to letter, J. E. Bower to C. Chasten (WES), June 17, 1992.

2 K. Hobens, Tainter gate strut arm bending at Lock and Dam No. 5, memorandum for record (with St. Paul District computation sheets), July 19, 1989.

*a. Member or component deformation.* Local web and flange plate buckling on the strut arms adjacent to the knee brace intersection from the upper horizontal girder was visible on several gates and is most severe on gate No. 24. The condition has not deteriorated since the last inspection and was most likely caused by excessive ice loads on the structure.

*b. Seal problems.* Water was observed flowing through the side seals.

*c. Rivet deterioration.* Corrosion and a small amount of section loss was visible on some rivet heads.

*d. Mechanical/electrical problems.* At gate No. 25, one chain hoist was out of its guide on the skin plate. This hoist was towards the Minnesota side of the gate.

*e. Fabrication defects.* There was no previous indication that fabrication defects existed in the structural members, and none were observed during this inspection.

*f. Corrosion.* Paint loss and blistering were visible along the top surface of the web on the upper horizontal girder under the diversion plate. Blistered paint was left intact during the inspection.

*g. Fatigue cracking.* No fatigue cracks were observed.

*h. Vibration or other unusual behavior.* To check for vibration, a test was conducted with the aid of a lockman. Gate No. 23 was fully closed and then reopened approximately 0.1 ft when vibration began normal to the face of the gate. By rough measurement, the vibration frequency was estimated at 5 to 10 Hz. The amplitude of vibration was maximum at midspan of the gate and was sufficient to create an audible noise and make ripples in the backwater. The vibration ceased when the gate was opened further.

*i. Application of unusual loads.* No unusual or extreme loads were reported. There was, however, an extensive accumulation of debris on the structural members in back of the skin plate, primarily large timber pieces.

**Assessment.** Because several detrimental conditions were detected during the inspection, the structural integrity of the spillway gate under normal operating conditions must be assessed. The assessments include the following:

*a.* Since the amount of local buckling on the strut arms has not increased since the last inspection and no sign of global buckling was observed, it is believed that neither the structural capacity of the buckled members nor the structural capacity of the gate is in jeopardy at this time.

*b*. The amount of water leakage from the side seals is considered tolerable and will have no effect on normal gate operations.

c. Misalignment of the chain hoist is not severe enough to jeopardize operation of gate 25, but should be corrected.

*d*. Deterioration due to corrosion and rivet head loss are considered minor and will have no effect on normal gate operations or gate strength.

*e*. Although flow-induced structural vibrations can cause serious damage to the spillway gate, previous field studies have calculated stress ranges of approximately 4 ksi (USACE 1986). Although this stress range is below the 6-ksi threshold for fatigue crack growth at riveted details, the presence of groove welds to water-seal gaps between adjacent skin plates and tack welds to attach the diversion plate to the gate ribs may reduce this threshold stress range. However, since no fatigue cracks were detected and it is known how to control the gate vibrations, the structural capacity is not in jeopardy.

*f*. Although the accumulation of debris on the gate structure has not caused any structural or corrosion problems, it should be removed.

**Recommendations.** Based on the assessment of conditions for the riveted tainter gates at Lock and Dam No. 5, the following recommendations are provided as steps that should be taken to ensure structural integrity for normal operations until the next regular inspection:

*a*. Operation of the spillway gates outside of the range which causes vibration should be continued.

*b*. Maintenance at gate 25 to make repairs or adjustments to reinstall the chain hoist in the guide on the skin plate should be scheduled.

c. Maintenance to remove large debris from all gate structures should be scheduled.

*d*. The buckled strut arm members should be occasionally monitored by lock personnel to detect any increases in deformation or distress to adjacent components.

*e*. Gate vibrations should be monitored by lock personnel to detect any changes and the inspection interval should be reduced to 2 to 3 years.

## Example 2

Let it be assumed that during the inspection of tainter gates at Lock and Dam No. 5 it was reported that a more significant mode of vibration had recently been observed by Corps personnel. Because of this new information, a thorough inspection was made at all fatigue-sensitive details on several gates where this vibration was observed. However, no fatigue cracks were visible.

Based on the inspection findings in this assumed example, a field study was recommended to determine the significance of these new vibrations. The results of the field study revealed that vibrations of approximately 5 cps (Hz) were producing cyclic stresses of up to 8 ksi at several fatigue sensitive details on the riveted structure.

The integrity of the riveted gate structure must be assessed by determining the fatigue strength of the details which are subjected to these cyclic loads. To evaluate the remaining fatigue life of the members, the procedures recommended in Chapter 5 will be followed. Since the measured maximum stress range is less than 10 ksi, the Category C curve will be used to determine the approximate number of cycles to failure at the detail (this does not imply that the entire structure will fail). By projecting lines on the $S_r$ - N Curve shown in Figure 31, it can be determined that the number of cycles to failure is approximately 12.5 million. With the measured frequency of vibration equal to 5 Hz, it would take approximately 694 hr (29 days) of vibration at this stress range to exceed the fatigue strength of the riveted connection. But because this new mode of vibration has only recently been observed, it is probable that not many cycles have accumulated to date. In fact, unless the gates in this assumed example are allowed to vibrate for extended periods, it may take up to 3-1/2 years before fatigue cracks develop if vibrations are limited to 1/2 hr per day while the gates are being adjusted.

The recommended action to address this assumed condition would consist of the following three steps:

*a*. Minimize the occurrence of gate vibrations by operating outside the range which causes vibration.

*b*. Reduce the inspection interval to approximately 1 year and inspect a greater number of gates to ensure that any fatigue cracks will be detected early.

*c*. Begin engineering studies to determine solutions which reduce the stresses caused by these vibrations.

## Recommendations for Continuing Evaluations

In Chapter 5, some quantitative guidelines were presented for evaluating fatigue strength of riveted gate members. In Chapter 4, however, quantitative guidelines were not presented for evaluating the effects of corrosion, a strong reason being that corrosion loss data and corrosion maintenance data for the gates were not available for this study.

It is suggested, though, that a quantitative index for corrosion effects can be developed. Such an index has been developed for steel girder bridges as a consequence of notable highway bridge failures and is based on reliability concepts (Kayser and Nowak 1987, 1989). The approach involves a sensitivity analysis for critical items, statistical (Bayesian) updating of the evaluations, and reliability analyses for safety. The Corps, too, has developed a similar reliability-based index, particularly to evaluate the corrosion of steel sheet piling (Mlakar et al. 1989). And, whereas, steel sheet piling is reportedly included in less than 30 percent of the structures operated by the Corps, spillway gates are reportedly included in over 50 percent of the structures operated by the Corps (Mlakar et al. 1989). Thus, the potential benefit of such a study for spillway gates is high.

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Guidelines are presented for structural inspection and evaluation of riveted spillway gates. An overview of the structural systems of most common types of spillway gates is also provided along with identification of critical areas that may be subject to degradation from corrosion and/or fatigue damage for each type of gate. Observations from site inspections at four locks and dams are included.

The principal factors contributing to corrosion and fatigue degradation of spillway gates are presented. Guidelines are also provided for the evaluation of corrosion and fatigue damage.

A structural inspection and evaluation procedure is outlined. The procedure consists of four components: preinspection assessment, inspection, assessment and recommendations for inspection maintenance and repair. For each component, the critical question to be addressed and the factors that must be considered are provided. Critical areas and techniques for inspection and reporting are discussed along with evaluation procedures. Two example inspections and evaluations are provided to illustrate the procedures.

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